DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES LIST

SECTION 11: LASERS, OPTICS AND SENSORS TECHNOLOGY

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PREFACE

A. THE MILITARILY CRITICAL TECHNOLOGIES PROGRAM (MCTP)

The MCTP supports the development and promulgation of the congressionally mandated Militarily Critical Technologies List (MCTL) and the Developing Science and Technologies List (DSTL).

Congress assigns the Secretary of Defense the responsibility of providing a list of militarily critical technologies (the MCTL) and of updating this list on an ongoing basis. The MCTL identifies technologies crucial to weapons development and has been a key element in evaluating U.S. and worldwide technological capabilities. The MCTP has provided the support for a wide range of assessments and judgments, along with technical justifications for devising U.S. and multilateral controls on exports. The DSTL, another MCTP product, identifies technologies that may enhance future military capabilities and provides an assessment of worldwide science and technology (S&T) capabilities.

The MCTP process is a continuous analytical and information-gathering process that refines data and updates existing technology lists to provide thorough and complete technical information. It covers the worldwide technology spectrum and provides a systematic, ongoing assessment and analysis of technologies and determines values and parameters for these technologies.

Technology Working Groups (TWGs), which are part of this process, provide a reservoir of technical experts who can assist in time-sensitive and quick-response tasks. TWG chairpersons continuously screen technologies and nominate items to be added or removed from the MCTL and DSTL. TWG members are subject matter experts (SMEs) from the military Services, DoD and other federal agencies, industry, and academia. A balance is maintained between public officials and private-sector representatives. TWGs collect a core of intellectual knowledge and reference information on an array of technologies, and these data are used as a resource for projects and other assignments. Working within an informal structure, TWG members strive to produce precise and objective analyses across dissimilar and often disparate areas. Currently, the TWGs are organized to address 20 technology areas:

Aeronautics	Information Systems
Armament and Energetic Materials	Lasers, Optics, and Sensors
Biological	Processing and Manufacturing
Biomedical	Marine Systems
Chemical	Materials and Processes
Directed Energy Systems	Nuclear Systems
Electronics	Positioning, Navigation, and Time
Energy Systems	Signature Control
Ground Systems	Space Systems
Information Security	Weapons Systems

B. THE MILITARILY CRITICAL TECHNOLOGIES LIST (MCTL)

The MCTL provides a coordinated description of existing goods and technologies that DoD assesses would permit significant advances in the development, production, and use of military capabilities by potential adversaries. It includes goods and technologies that enable the development, production, and employment of weapons of mass destruction (WMD) and their means of delivery. It includes discrete parameters for systems; equipment;

subassemblies; components; and critical materials; unique test, inspection, and production equipment; unique software, development, production, and use know-how; and worldwide technology capability assessments.

C. LEGAL BASIS FOR THE LIST OF MILITARILY CRITICAL TECHNOLOGIES

The Export Administration Act (EAA) of 1979 assigned responsibilities for export controls to protect technologies and weapons systems. It established the requirement for DoD to compile a list of militarily critical technologies. Specifically the EAA stated:

"(5)(d)(2) The Secretary of Defense shall bear primary responsibility for developing a list of militarily critical technologies. In developing such list, primary emphasis shall be given to—

(A) arrays of design and manufacturing know-how,

(B) keystone manufacturing, inspection, and test equipment,

(C) goods accompanied by sophisticated operation, application, or maintenance know-how, and

(D) keystone equipment which would reveal or give insight into the design and manufacture of a United States military system, which are not possessed by, or available in fact from sources outside the United States to, controlled countries and which, if exported, would permit a significant advance in a military system of any such country.

(3) The list referred to in paragraph (2) shall be sufficiently specific to guide the determinations of any official exercising export licensing responsibilities under this Act."

The EAA and its provisions, as amended, were extended by Executive Orders and Presidential directives.

D. USES AND APPLICATIONS

The MCTL is not an export control list. It is DoD's recommendation for what should be controlled. When goods are identified as being militarily critical, the technology for the development or production is also recommended for control. The document is to be sufficiently specific for evaluating potential technology transfers and has been used for reviewing technical reports and scientific papers for public release. Technical judgment must be used when applying the information. It should be used to determine if the proposed transaction would result in a transfer that would give potential adversaries access to technologies whose specific performance levels are at or above the characteristics identified as militarily critical. It should be used with other information to determine whether a transfer should be approved.

This document, MCTL Section 11: Lasers, Optics and Sensors Technology supersedes MCTL Section 11, Lasers, Optics and Imaging Technology, December 2005 and MCTL Part 1, Sections 15.1, 15.2, 15.3, 15.4 and 15.10

INTRODUCTION

A. ORGANIZATION OF THE MILITARILY CRITICAL TECHNOLOGIES LIST (MCTL)

The MCTL is a documented snapshot in time of the ongoing MCTP militarily critical technology process. It includes text and graphic displays of technical data on individual technology data sheets.

Each section contains subsections devoted to specific technology areas. The section front matter contains the following:

- *Scope* identifies the technology groups covered in the section. Each group is covered in a separate subsection.
- *Highlights* identify the key facts in the section.
- *Overview* discusses the technology groups identified under "Scope."
- *Background* provides additional information.

Each technology group identified under Scope has a subsection that contains the following:

- *Highlights* identify the key facts found in the subsection.
- *Overview* identifies and discusses technologies listed in data sheets that follow.
- *Background* provides additional information.
- *Data Sheets,* which are the heart of the MCTL, present data on individual militarily critical technologies. The principal data element is the Critical Technology Parameter, which is the technology parameter that defines where the technology would permit significant advances in the development, production and use of military capabilities of potential adversaries.

B. TECHNOLOGY DATA SHEETS

The technology data sheets are of primary interest to all users. They contain the detailed parametric information that export control policy makers and licensing officials need to execute their responsibilities.

- *Critical Technology Parameter(s)* includes the parameter, data argument, value, or level of the technology which would permit significant advances in the development, production and use of military capabilities of potential adversaries.
- *Critical Materials* are those materials that are unique or enable the capability or function of the technology.
- *Unique Test, Production and Inspection Equipment* includes that type of equipment that is critical or unique.
- *Unique Software* is software needed to produce, operate, or maintain this technology that is unique.
- *Major Commercial Applications* addresses commercial uses of this technology.
- *Affordability Issues* are those factors that affect the cost of the technology.
- *Export Control References* indicate international and U.S. control lists where this technology is controlled.

  Note: Export control references are:

WA ML 2	(Wassenaar Arrangement Munitions List Item)
WA Cat 1C	(Wassenaar Dual Use List Subcategory)
MTCR 17	(Missile Technology Control Regime Item)

NTL B3	(Nuclear Trigger List Subitem – Nuclear Suppliers Group)
NDUL 1	(Nuclear Dual Use List Item – Nuclear Suppliers Group)
AG List	(Australia Group List)
BWC	(Biological Weapons Convention)
CWC	(Chemical Weapons Convention)
USML XII	(United States Munitions List Category – ITAR)
CCL Cat 2B	(Commerce Control List Subcategory – EAR)
NRC A	(Nuclear Regulatory Commission Item)

- *Background* provides a description of the technology.

SECTION 11—LASERS, OPTICS AND SENSORS TECHNOLOGY

Scope

Highlights

Lasers

- The battlefield efficiency and utility of modern military systems and platforms including armor, aircraft, missiles, and infantry has been greatly increased through the use of high efficiency lasers for: targeting, ranging, designating, communicating, enhanced imaging, night time illumination and weapons.
- High-power solid-state lasers and the oxygen iodine laser have had significant technology advances to improve efficiency and reduce weight so that now they require much smaller volumes with greater output than previously thought feasible, making them much more useful for battlefield applications.
- New laser technology products including fiber lasers and very high efficiency (> 70%-wallplug efficiency) semiconductor lasers in the near infrared and mid-infrared are now making a significant impact on both commercial and military applications.

Optics

- Lightweight, high-stiffness, precision optical components, using composites and metallic foams, are now available with an "areal density" (surface density) of < 10 kg/m^2 (with goals of less than 5 kg/m^2), significantly reducing the weight of aerospace surveillance optics and high energy laser optics.
- Real-time, computer-controlled optical grinding and polishing, along with micropolishing have cut the time (costs) required to fabricate aspheric optics and conformal optics by a factor > 10.
- Micro-optics and micro-opto-electro-mechanical systems (MOEMS) have begun to complement and replace optical and electronic components on chips, reducing heat, improving speed and throughput while reducing cost and weight.

Optical Materials

- Stronger optical materials in combination with more efficient optical coatings provide more effective protection for optical elements and sensors in hazardous and thermally stressful atmospheric conditions.
- Significantly improved nonlinear optical materials can shift the wavelengths (or frequency) of radiation to more desirable levels and enhance the operation, enabling optical parametric oscillators and tunable laser systems with much higher power level capability.
- Sintered ceramic materials provide extensive improvements in optical properties, including solid-state laser rods with operating parameters exceeding those of current single crystal lasers, and higher peak powers, increased rod sizes, and higher rare earth doping densities.

(Continued)

Electro-Optical Sensors

- Uncooled focal plane arrays (FPAs) are very significant militarily because of lower cost, size and weight.
- 2nd-generation forward-looking infrared (FLIR) component are replacing the modular FLIR components in many military applications.
- 3rd-generation FLIRs have large area, dual-band FPAs operating in both the Mid Wave Infra Red (MWIR) and Long Wave Infra Red (LWIR) regions.

Marine Acoustic Sensors

- In modern undersea warfare at sea, the side with superior acoustic sensors has a great advantage over their adversaries in both pro and anti surface ship, submarine, torpedo and mine (undersea) warfare.
- Active acoustic sensors are used to obtain massive amounts of real-time, highly accurate data while passive sensors are used for covert type operations.
- Improved acoustic sensor performance is required for offsetting or countering the stealthy fuel cell/diesel-electric submarines being introduced worldwide and the need for the U.S. Navy to operate more in littoral areas.
- Acoustic sensor performance can be improved by:
  - Multiple, unique interference-rejection techniques, including active platform noise cancellation.
  - Advanced statistical signal processing techniques.
  - Advanced innovative new techniques for single and volumetric towed arrays.
  - Automated information management, including using more robust discrimination between targets and target-like false targets and more complex and correct decision criteria, both using robust decision theoretic approaches.
  - Deployed systems consisting of an array of hydrophones laid out in a random pattern in a strategic operating area working in the passive mode as well as with an independent sound source for bi-statically detecting stealthy submarine targets in open ocean and littoral areas.
  - Fusion of raw sensor data and coherent data from multiple sensors and platforms, including using network centric warfare techniques.
- Multiple sensors are required to rapidly detect and neutralize sea and littoral region mines with higher probability of correct decisions and minimum false alarms.
- It is envisioned that evolutionary improvements in acoustic sensor systems will continue.

Radar Sensors

- Radar will remain a primary capability for all-weather/day-night surveillance, detection, acquisition and tracking of non-cooperative targets.
- Advances in microwave technologies, particularly in the area of solid state devices, has increased the global availability of critical components for fabricating advanced radars, including electronically-steerable phased array radar.
- However, effective application of such technologies demands detailed empirical knowledge of the phenomena associated with atmospheric propagation, environmental effects (clutter) and target signature characteristics as a function of microwave parameters.
- While other countries have significant capabilities, none has, as yet, anything approaching the U.S.'s base of experimental data based on substantial numbers of diverse radar developments, particularly in the area of phase array radar.

OVERVIEW

A. LASERS

This section covers militarily critical technology for lasers, along with their specifically designed supporting technologies. The primary goal in this section is to identify and list laser technologies that could conceivably result in (1) major improvements in currently available military laser/optics systems and components; (2) the development of significantly new cost-saving approaches to the generation of both low-power and high-power laser sources; (3) the development of higher efficiency, lightweight laser components and systems; (4) the development of information technology and telecommunication laser components; and (5) the development of micro- and nanotechnology as pertains to lasers. The key issue for determining if a technology is militarily critical is whether the technology would provide significant capability to an adversary.

This section includes high-energy lasers, high-power lasers and low-energy laser systems. The high-energy laser/low-energy laser cutoff is nominally considered to be 20 kW of average output power. High-power lasers are designated as those that produce a continuous wave power level in excess of 20 kW peak pulsed power. The output of a laser can be pulsed or a continuous beam in the visible, infrared (IR), or ultraviolet spectrum. It can be less than a nanowatt to many millions of watts of power. Technologies applicable to the development and production of lasers and laser systems in the IR, visible and ultraviolet regions of the electromagnetic spectrum (0.1 μm to 30 μm) capable of achieving militarily significant levels of energy or power will be covered as well.

Note that the systems technologies for high-energy laser (HEL) systems are covered in the "Directed Energy Systems" Section 6 of the MCTL, but the laser technologies that are used in those systems are covered in this section.

B. OPTICS

The optics technologies listed in this section cover the broad discipline area of optics and optical component technologies, which are mature and of critical military utility today or within the next five years. This section also includes militarily critical composite optical components.

They are being developed to improve efficiency, provide longer life expectancy, reduce costs, and replace outdated technology in other application sectors such as electronics. Optical communications and optical memory storage are just two areas in which optics is rapidly replacing electronic components; however, these specific optical technologies are application dependent and are covered in either the Electronics Technology section or the Information Systems Technology section of the MCTL where appropriate.

Note: Space unique optics and related technologies are covered in the "Space Systems Technologies" section of the MCTL.

C. OPTICAL MATERIALS

This section includes optical materials and optical material technologies for linear and non-linear materials with transmission in the ultra-violet (UV), visible and infrared (IR) spectral regimes. This sub-item includes both bulk materials and thin films and coatings. Depending on the application, these materials/coatings may be required to filter either broad or narrow bands and in some cases they are required to be "frequency agile," i.e., have the ability to shift their frequency range as a function of internal or external stimuli. Special emphasis is placed on materials and coatings which are affordable, maintainable and durable in harsh environments experienced in military operations, such as, exposure to high speed rain and dust, and/or high temperatures and/or high structural loads associated with high speed, maneuvering flight.

This section has been divided into (a) IR windows; domes and protective coatings; (b) specialty transparent materials (coatings and filters); (c) nonlinear optical materials for wavelength conversion; (d) high energy laser (HEL) optical components (mirrors, windows, beamsplitters); (e) optical sensor materials, electro-optical sensors (materials for cooled and uncooled arrays); (f) laser materials (solid-state tunable lasers, fiber lasers, and sintered ceramics); (g) passive optical limiting materials; and, (h) active wavelength filtering materials.

In most cases, the mission requirements of individual weapons platforms and their associated optical systems dictate the specific capability of the optical materials and coatings in the components thereof. Capability not only refers to the accuracy of the system or sensor component, but it can include such "ilities" as mission environment, durability, availability and cost of ownership. A key breakpoint in IR window technology occurs at strengths greater than 7 ksi and materials/coatings that are resistant to rain/dust erosion at speeds above Mach 1.0 and survive aero-thermal heating at a rate > 100 W/cm^2. A key breakpoint for wavelength conversion applications in the 2- to 12-micrometer spectral band occurs at average output powers greater than 2 W.

Because of factors such as the much higher level of sensitivity and the severity of the environment required in military operations as contrasted with commercial needs (e.g., the automobile industry), most of these technologies are not strong candidates for dual use. As an example, a major driver for some of this technology is rain and dust erosion on exposed optical surfaces which becomes a factor at speeds greater than 350 to 400 miles per hour (mph), whereas, the auto needs are limited to less than about 100 mph. Also, factors involving EO countermeasures are peculiar to the military. As an exception, some of the nonlinear optical materials will likely be utilized in lasers for detection and identification of chemical species in environmental pollutants, and some cheaper, less sophisticated forms of the linear optics coating technology could be adapted by the automobile industry and commercial aviation for night vision (IR) sensors and other transparencies.

The accurate assessment of target location through surveillance and subsequent guidance and accurate delivery of WMD assets is critically linked to the durability and survival of the optical sensor/seeker systems onboard the delivery platform and the munition. Both must endure adverse environmental and hostile conditions such as rain and dust and EO countermeasures, often at supersonic speeds. These capabilities are provided, in part, by optical materials and/or coatings and directly determine the delivery accuracy and lethality of manned and unmanned, guided weapons systems. Access to materials and coating technology would amplify threats to regional stability to a critical extent by making available to hostile forces a much superior material and/or optical coating/filter for windows, domes and optical elements for optical (EO) sensor systems. The current U.S. technology lead translates into a combat and performance advantage for U.S. military forces and, therefore, these technologies need to be protected.

D. ELECTRO-OPTICAL SENSORS

"Night Vision" is normally considered to embrace two different technologies, image intensification and thermal imaging. Image intensification, which depends on reflected light from objects in the scene, developed earlier than thermal imaging, which depends on blackbody radiation from objects in the scene. Surveillance sensors, which are used by astronomers and military alike, are also outlined in this section.

Imaging with Reflected Photons. Image intensification, as it exists in the latest 3rd-generation tubes used in aviation goggles has the highest performance available in the operational inventory. A recent modification of 3rd-generation tubes improves the performance of image intensifiers when there are bright sources in the scene. These sources tended to mask part of the scene in earlier generations of the tubes.

Thermal Imaging. Thermal imaging systems for terrestrial applications deployed in the late 20th century, operated primarily in two spectral wavelength regions, mid-wave infrared 3–5 μm and long wave infra red (long-wave infrared) 8–11 μm. These systems originally depended on cooled detector arrays for peak sensitivity but in the 1990s detectors were developed that required minimal or no cooling. Although cooled arrays have higher sensitivity than uncooled detector arrays, many applications are not possible with the cooled arrays. With no cooling engines that consume power, lightweight, affordable systems such as personal viewers and vehicle driving aids are possible. A number of civil applications are appearing because of the lower cost. Early thermal-imaging systems used scanned linear arrays and much of the operational inventory has these systems. Second-generation systems having up to about 2,500 detector elements in a two-dimensional array are now replacing the linear arrays that used a maximum of 240 elements. Staring systems developments are underway, and most planned systems will employ staring arrays that require no mechanical scanning. Third-generation systems have 640 × 480 pixels, or greater, staring FPAs in the MWIR/LWIR regions. These sections on lasers, optics, and sensors outline technologies that are currently used or will be used within a five-year time frame for all of the above technical areas. The military applications include laser weapons, missile guidance, range finding, optical information processing, optical filters, optical displays, sensing, and illumination, as well as associated technologies in optical and laser components and materials. Each of these is listed in appropriate subsections as independent technology items.

E. MARINE ACOUSTIC SENSORS

This section includes the technologies for the development and production of all acoustic sensors (sonars) that are the primary undersea warfare sensors of military interest. This section also includes the technologies for the development and production of all acoustic sonars for commercial applications. Acoustic sensors, both military and commercial, employ acoustic signals to echo range or listen to and detect, track, classify and locate underwater objects, including determining the depth of the ocean and highlighting bottom and sub-bottom features. It contains information on data processing for both single and multi arrays using data fusion, helicopter dipping sonars, sonobuoys, deployed array sonars, underwater weapons and on underwater acoustic mine countermeasures.

Acoustic sensors are already vital and will become even more so in the future for effective and safe undersea warfare operations, regardless of whether for open conflict, peace keeping and training or humanitarian efforts. No single sensor approach has been demonstrated to be effective in finding marine mines, but acoustic sensors remain dominant. Acoustic sensors are also vital for many civilian endeavors as well, primarily for petroleum and mineral exploration and exploitation, underwater cable laying and maintenance and fish finding. It is envisioned that evolutionary improvements in acoustic sensors will continue.

F. RADAR SENSORS

This section addresses radar technologies at the level of integrated systems and critical enabling subsystems. Coverage ranges from UHF radar used for over-the-horizon targeting to millimeter wave tracking radars for fire control.

Technologies for applications of radar to specific mission functions are also addressed elsewhere, as follows:

- Radar sensors for target detection and fuzing, including proximity sensors and precision height-of-burst radar altimetry—Section 2.3, Safing, Arming, Fuzing, and Firing (SAFF);
- Millimeter Wave Radar, and Laser Radar for Terminal Guidance and Control—Section 2.5, Guidance and Control; and
- Ground Penetrating Radar for Countermine Detection—Section 2.9, Mine/Countermine Technology.

Technology for radar mapping and digital scene correlation, also applicable to land attack missile guidance and control, have also emerged as an element of precision positioning and navigation (Section 16) database reference navigation (RN).

BACKGROUND

A. LASERS

Lasers and laser optics constitute a diverse body of technologies. Since the discovery of lasers in 1960, there has been an exponential growth of laser and laser-related technology. The U.S. military led the charge in laser development during the 1960s and on through the 1990s in the various government laboratories. Over the years, the laser optics industry has found many commercial applications that justify corporate funding, resulting in broad-based industry involvement today.

The development of the ruby laser in 1960 provided resurgence to optics and the field of electro-optics. Lasers and optics have become a key part of everyday life such as the scanner at the grocery checkout counter or the lasers used in compact disk (CD) recorders and players. Lasers have satisfied many needs and solved many requirements for special military applications and new advanced laser technologies are anticipated to make many significant improvements in the future as well. Early laser research workers had visions of firing lasers at missiles and destroying other targets with a speed-of-light weapon. It has taken many years (some 30+) to demonstrate such a capability, but a tactical capability to engage with lethal effects at ranges up to 2 km has been successfully demonstrated. A capability against boosting theater and ICBM class missiles has yet to be demonstrated. The ABL technology demonstration is scheduled to demonstrate this capability in the near future.

The laser weapon concept has been demonstrated both on the ground and in airborne configurations, but there are numerous technical challenges that must be solved. At first glance, high-power lasers would seem to serve only military needs, but advances in these technologies have provided many other uses for scientific and commercial applications. Many challenges in the high-energy laser technology area remain, however. The National Research Council's report "Harnessing Light" (1998) lists the following technical challenges for high-power lasers:

- Stabilized optical resonators under high thermal loading conditions.
- Producing high optical quality, near-diffraction-limited beams with high efficiency.
- Improved propagation by suppressing nonlinear optical effects along the propagation path.
- Improved adaptive optics to correct for beam distortions during propagation.
- Solving operational issues such as environmental factors and lethality for different target classes.

B. OPTICS

Optics and laser technologies have matured in the specialized telecommunications information-technology arenas and in three-dimensional image storage devices. Optics and electro-optics research technologies are now the predominate emerging technologies in the laser optics disciplines. In addition, new designs for lightweight optics are needed and being developed for helmet-mounted displays as well as for aerospace optics.

A new area of research in which optics and lasers are playing a vital role is in micro-electro-mechanical systems (MEMS). MEMS and MOEMS technology are starting to revolutionize the way we live—in both the civilian and military sectors. MOEMS devices with motors and repositioning mirrors have been constructed for use with other "on-chip technology." Lasers have joined the MOEMS family, and now these new on-chip technologies have moved into another phase.

C. OPTICAL MATERIALS

There are many limitations for optics and laser devices due to materials issues and manufacturing process issues as well as systems engineering issues. This section will outline the materials that are currently under product development for military applications.

Quality optical materials are essential for the successful completion of many military missions. The following structure provides a useful way for organizing materials according to their characteristics and functions in applications.

1. Window materials are used to isolate two physical environments while allowing light to pass. Window materials serve to protect delicate sensors from harsh external operating environments. Such materials must therefore match high optical transparency with high mechanical and thermal strength. Examples of situations that require window materials are vacuum or space-based sensors, and seeker windows in high-speed missile sensors.
2. Optical elements include devices such as lenses, prisms, beamsplitters, mirrors, polarization components and filters that are used to modify a beam of light. The materials used for all of these elements must be of the highest optical clarity and uniformity, and must be capable of maintaining their optical properties at very high power densities. Lens elements are used in many applications such as telescopes, collimators, magnifiers, and optical transceivers. Prisms are used in optical systems to deflect a light beam. They can invert or rotate an image, disperse light into its component wavelengths, and be used to separate polarization states. Beamsplitters are used to separate a light beam into two separate paths. Filters are used to attenuate light intensity at desired wavelengths, by absorption of radiation in the filter material or by utilizing the interference properties of optical thin film coatings applied to a substrate.
3. Optical thin film coatings are used to modify the reflection and transmission properties at the surface of the optical element. Thin film coatings can reduce reflections at lens surfaces, allowing more light to reach the sensors behind the lens, and can also block unwanted wavelengths. Applications for thin film coatings include disease diagnosis, spectral radiometry, calorimetry, and color separation in cameras. They can also be used to physically protect an optical element comprised of a soft window material from scratching, staining, or other physical damage.

4. Adhesives—Optically clear, high strength adhesives are used for connecting optical components and to provide heat and moisture resistance.

5. Support for optical elements—Beryllium is replacing glass in some large-aperture space and ground telescopes for high resolution military systems, and is desired in the nose cones of missile interceptors and in lightweight optical subsystems for satellite sensors due to its lightweight, excellent thermal properties for rapid cooling, and extremely high specific stiffness. Graphite composite also is lightweight with high dimensional stability, and is useful for supporting structures for optical elements.

6. Opto-electronic materials—Detector materials for infrared, visible, and ultraviolet wavelengths convert optical energy into electrical signals that can be transmitted, analyzed and processed electronically before being presented to a user as imaging or targeting data. A variety of active opto-electronic materials are used to convert the photons emitted or reflected by a target into useful electronic signals. Semiconductors such as germanium, gallium arsenide, and mercury cadmium telluride are sensitive to infrared and visible wavelengths, and photomultipliers are useful for visible and ultraviolet detection. Thermistor materials such as vanadium oxide sense thermal radiation with decreases in electrical resistance.

7. Laser materials—High-energy solid-state lasers use transparent crystals, sintered ceramics, or glasses doped with impurity atoms to create high-power laser line emission at a variety of IR wavelengths. Solid crystals of high-strength, optically transparent material with good thermal properties, such as sapphire or yttrium aluminum garnet (YAG) are doped with metal atoms such as chromium, neodymium, or erbium to produce laser rod materials. These rods can be shaped and polished to yield high-power solid-state lasers with applications for rangefinding, laser radar, and infrared countermeasures. Polycrystalline ceramic materials such as Y2O3 have recently shown promise as alternative materials for high-energy solid-state laser gain elements. Ceramics are formed at lower temperatures and can contain higher concentrations of the rare-earth dopants that generate laser gain than single-crystal materials. Additionally, rare earth doped single mode silica fibers may be used as laser gain materials.

8. Wavelength conversion materials—Military applications such as data storage, communications, and laser based imaging are often wavelength specific and require methods to produce coherent radiation at a desired wavelength. The use of nonlinear optics to adapt lasers for wavelength specific applications has created a need for new, efficient, easily grown and damage resistant nonlinear optical materials. Well developed materials exist for frequency conversion of such lasers as Ng:YAG, but materials having higher conversion efficiencies are desired. Some optical materials with strongly nonlinear behavior at IR frequencies include potassium titanyl phosphate, BaB_2O_4 (BBO crystal), and $AgGaS_2$. These materials are useful for converting an input laser's radiation to longer wavelengths (lower energy) that can be tuned continuously over a large frequency range.

9. Eye and sensor protection materials—Selectively transparent materials capable of statically or dynamically protecting soldiers' eyes and sensitive detector elements from high-power laser radiation on the battlefield can be constructed from a variety of materials. Passive bulk filter materials and selectively fabricated thin film coatings can block known laser wavelengths, and active filter materials such as non-linear optical materials, or nematic or cholesteric liquid crystals, can block all wavelengths that exceed a specified power density.

10. Obstructive materials—Absorbing or scattering materials can be used to obscure valuable targets and confuse or jam enemy sensor arrays. Obstructive materials can include fog-oil or smoke particles with diameters close to the wavelength of visible light, or other materials such as graphite flakes and brass powders tailored to scatter or absorb specific infrared wavelengths.

11. Fiber optics designed for SWIR, MWIR, and LWIR laser transmission—Specialized glass and hollow-core fiber optic materials have been developed for the transmission of laser energy at infrared wavelengths where standard fiber optic materials are not transparent. Chalcogenide and heavy metal fluoride glasses, sapphire crystals, and hollow glass waveguide structures have all been used to carry infrared laser energy over short distances, but losses remain high for long distance (> 1 m) transmission. Infrared fiber optics have uses for laser power delivery, thermal imaging, radiometery, and chemical sensors.

D. ELECTRO-OPTICAL SENSORS

A rudimentary form of image intensification existed in the 1940s and 1950s. It was possible to view scenes at night using image converters and IR active illuminators. The early active systems of this time used IR sources, such as filtered searchlights. These still radiated considerable visible energy and were not covert. The development of cascaded, electrostatically focused image intensification and the S-20 photocathode in the 1960s eliminated the need for active illumination, creating a covert or passive viewer.[1] The Starlight Scope, deployed first in Viet Nam, was the forerunner of an extensive family of intensified night viewing equipment. The most recent manifestation of this technology is the night vision goggle used by both ground troops and aviators. The original passive intensifier required three cascaded devices, each with a gain of about 40, to achieve enough light gain to be passive. The goggle tube uses a microchannel amplifier that provides the same gain as three older tubes. The 3rd-generation tubes use a GaAs photocathode, with higher gain and production yield than the S-20/25 multialkali photocathodes.

A newer technology is now available known as Electron Multiplying Charge-Coupled Devices (EMCCDs). These devices can be substituted for the MCP in image intensifier tubes and this provides a video output instead of a phosphor screen. In this application the EMCCD is responding to electrons from a photocathode.

EMCCDs also exist that respond to visible and infrared photons and can provide a low light level, solid-state sensor.

Thermal imaging systems were deployed experimentally in Viet Nam; the best known equipment was the early FLIR equipment deployed on the C-47 and C-130 Gunships. Thermal-imaging systems are now widely deployed operationally (in the late 1990s). These systems range from large, shipboard infrared search and track (IRST) systems down to miniature, handheld thermal viewers and include missile night sights and seekers, vehicle driving aids, and airborne FLIR.

Government applications for thermal-mapping sensors include:

- Military hyperspectral imagers,
- Missile seekers,
- NASA space systems,
- National missile defense,
- Remote sensing,
- Satellite imaging,
- Star trackers,
- Three-dimensional imaging,
- Wavefront correction, and
- Weather detection.

Commercial applications for thermal imaging sensors include:

- Agriculture,
- Astronomy—land- and space-based telescopes,
- Atomic/molecular spectroscopy,
- Chemistry and drug analysis,
- Commercial spectrometers,
- Environmental monitoring,

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[1] Electromagnetically focused intensifiers existed and were used by astronomers. They were far too large and power hungry for use in most military applications.

- Gas chromatography,
- High-end photo/video,
- Ice detection,
- Nondestructive evaluation,
- Satellite guidance and communication, and
- Wavelength division multiplexing.

E. MARINE ACOUSTIC SENSORS

The data obtained from acoustic sensors are a basic ingredient for all naval operational concepts in use now and projected for the future. They are vital to operations at both the tactical and strategic levels. They are needed to provide information during all phases of planning and operations. Active sonars are used to obtain massive amounts of real-time, highly accurate data. Passive sonars are used for covert type operations. In all undersea warfare scenarios, sonars will be used singly or in combination with one serving as primary and others used to confirm or verify the results. Sonars are used militarily in the marine environment for locating ships, submarines, torpedoes, ocean mines and objects lost at sea; and for weapons homing and activation. In modern undersea warfare, the side with the superior sonars has a significant advantage over their adversaries.

F. RADAR SENSORS

RADAR, initially from RAdio Detection And Ranging, is defined as:

> A device for transmitting electromagnetic signals and receiving echoes from objects of interest (targets) within its volume of coverage. Presence of a target is revealed by detection of its echo, or a transponder reply. Additional information about a target provided by radar includes one or more of the following: distance (range), by elapsed time between transmission of the signal and reception of the return signal; direction, by use of directive antenna patterns; rate of change of range; by measurement of Doppler shift, description or classification of targets, by analysis of echoes and their variation with time.

Radar has several features that ensure that it will remain a primary sensor for all-weather/day night surveillance, target acquisition and tracking for weapons assignment and control. Foremost among these is the ability to see through clouds and rain (in selected frequency bands), and to localize targets in three dimensions and determine target trajectory from a single sensor (i.e., without the need for triangulation with other sensors). Use of electronically steerable arrays further allows for simultaneous tracking of multiple targets while scanning.

SECTION 11.1—LASERS

Highlights

- The battlefield efficiency of modern (platforms), including space, armor, aircraft, missiles, and infantry, is being greatly increased through the use of improved high-efficiency lasers.
- High power solid-state lasers and improved oxygen iodine lasers have resulted from major technology advances that provide greater laser output in much smaller packages.
- The laser diode, which has had significant improvement in efficiency (> 70%), is now a key component in: medical equipment, space communication systems, fiber-optics transmission systems, optical sensor systems, battlefield surveillance, and sensor blinding.
- Rapid advances in the manufacturing technology of laser diode bars and arrays now used for pumping solid-state lasers are significantly improving the solid-state laser development for DoD mid IR CM, remote battlefield sensing, illumination, LRF/designators, and laser weapons. Both solid-state and semiconductor lasers are used on the battlefield to cauterize wounds and help stop blood flow.
- Lasers are now being embodied in military opto-electronics and MOEMS, reducing weight and improving performance.
- Laser technology has become a revolutionary tool for better understanding molecular physics, particularly in the fields of medicine and spectroscopy.
- Microchip and MOEMS lasers and photonic crystal lasers in nonlinear optical media are revolutionizing the current electronic and laser industries.
- Fiber lasers and quantum cascade lasers are the newest lasers to enhance both communications as well as battlefield weapons applications.

OVERVIEW

This section will address all lasers of military significance that have dual-use possibilities (commercial and military) as well as those specifically designed for laser weapons. However, nuclear isomer laser research, which has been suggested for gamma-ray lasers, although proceeding in the research phase has not been developed, and will not be included. Note, the lasers listed here are continually being investigated experimentally for improvements. New techniques are being applied to improve the performance of, or create laser devices that have better operating characteristics. In this regard, this section outlines the current parameters that are considered critical to military applications, but not those in the development stage that is expected to take more than five years. Those developing technologies are listed in the Developing Science and Technologies List (DSTL) section.

Lasers can be classified in several ways. For this section, the field has been classified by the type of active medium (host material) used in the laser: gas, solid-state, and semiconductors. Some laser concepts are based on special conditions of the lasing medium, which are more esoteric (i.e., free electron, gas dynamic, chemical transfer, nuclear isomer energy storage, and plasma flame).

Lasers, as defined for purposes of this section, consist of the laser hardware (the device) and the laser medium (or host material) and, in some instances, the power source and/or the cooling supply if these are specially designed for the laser. Lasers can operate in a continuous, repetitive burst or single-pulsed mode, depending on the application and requirements. Laser systems incorporate components such as amplifier stages, frequency conversion components, Raman cells, multiple-wave mixing components, or other major elements, in addition to the laser oscillator.

This section outlines developed or mature technologies or those nearly mature for militarily critical applications, including weapons, missile guidance, range-finding, optical filters, optical information processing, telecommunications, storage and transport, optical displays, sensing, and illumination. It also includes associated technologies in laser components and laser host materials currently under development for military applications. These lasers are listed in this section as independent technology items.

The primary goal of this section is to identify and list those technologies that are militarily critical and to identify the key critical parameter levels of each technology. Militarily critical implies that the technology would provide a significant capability to an adversary. The following is a list of key militarily critical parameters that have been identified as the basis for the militarily critical laser technologies listed:

- Major improvements in efficiency for currently available military laser systems and components.
- Significantly new cost-saving technologies to the generation of both low- and high-power coherent radiation sources and illuminators of military significance.
- Higher-efficiency, lightweight laser components and systems of military significance.
- Significant improvement in information handling and routing technology via lasers and telecommunication laser components utilized in military systems.
- Micro- and nano-technology, as they pertain to lasers for decreasing weight, increasing efficiency and durability, and reducing cost.

Both high-energy laser and low-energy laser system technologies that have militarily critical parameter levels are covered in this section. High-energy lasers are designated as those that produce a continuous wave or repetitive pulsed-average power level in excess of 20 kW; otherwise, the system is considered a low-energy laser. However, low-energy lasers can produce high peak powers in the pulsed mode. Note, both repetitive pulsed and continuous wave lasers can achieve high power levels exceeding many megawatts.

BACKGROUND

"Laser" is an acronym for light amplification by the stimulated emission of radiation. The term "laser" is generally used to describe any device that uses light amplification to create a coherent beam of monochromatic light. Usually, the laser device entails a pair of mirrors forming an optical resonator cavity, and a light-amplifying medium in between them (see Figure 11.1-1). The light-amplifying medium is generally a substance that has been excited so that the atoms or molecules, when struck by a photon of the right wavelength, will absorb and then release part of their energy in the form of another photon. Most of the photons can be directed via laser optics to stimulate the other atoms or molecules to emit photons that have the identical frequency, phase, and direction of propagation as that of the first photon emitted along the laser beam path.

The light beam produced by a laser is unique because all the photons are almost identical copies of each other, creating a uniform, spatially coherent wavefront that remains coherent spatially and temporally as it propagates through space. Therefore, this highly spatially coherent radiation can produce interference when spatially combined with another beam at the same frequency. Thus, laser light is quite different from ordinary light and, as a result, can be used in many unique applications such as holography, lithography, Raman cells, and dark field microscopy.

Lasers produce a beam of light that is nearly monochromatic and highly directional. In practice, however, one always observes light with a small spread of frequencies—even under the best conditions. The energy of a laser beam is nearly collimated (within diffraction limits) under normal conditions of a stable laser.

There are many different types of lasers and many different applications. These applications require different levels of energy in the beam or perhaps different pulse-time sequences. A laser pointer produces a spot on a wall that can be seen, and a high-powered industrial laser produces holes in thick metal within a few seconds. The most common electromagnetic laser cavity consists of two mirrors with circular apertures (see Figure 11.1-1). The reflecting surfaces are segments of spheres with radii, R_1 and R_2, and separated by a distance, L. The best alignment occurs when the line joining the centers of curvature is coincident with the geometrical axis through the mirror centers and the laser medium.

The development of the ruby laser in 1960 provided resurgence in the fields of optical radiation and electro-optics. Lasers have solved many requirements for military applications. And, advanced technologies are anticipated to make significant improvements in the future. Early laser research workers had visions of firing lasers at missiles and destroying other targets with a speed-of-light weapon. It has taken many years to demonstrate such a capability. Although airborne and space lasers are nearing final development, they have many limitations because of materials and manufacturing process issues.

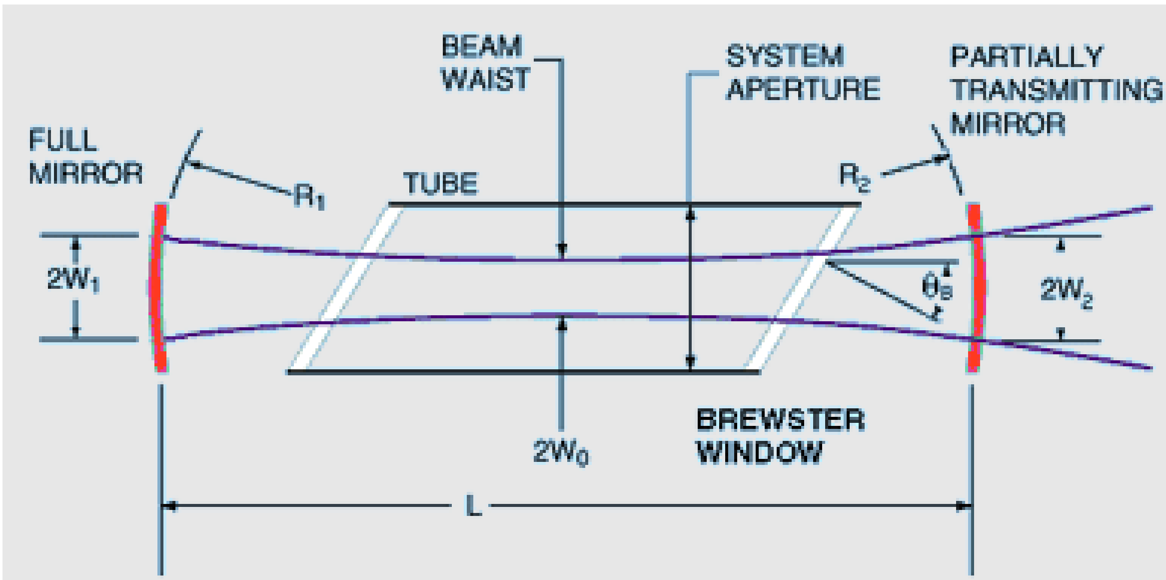


Figure 11.1-1. Cavity Mode Distribution of a Simple Gas Laser

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.1. LASERS

MCTL DATA SHEET 11.1-1. RARE EARTH DOPED NON–"TUNABLE" SOLID–STATE, CERAMIC, AND CRYSTALLINE LASERS

Critical Technology Parameter(s)	This technology includes all rare-earth doped non-tunable solid-state, ceramic and crystalline lasers with the following critical parameter levels. The critical technology parameters for these lasers vary with wavelength ranges and type of lasers as follows: 1. Having a fundamental output wavelength ≤ 800 nm, as follows: • Lasers having a pulse duration < 1 ns and having any of the following: a. A peak power ≥ 5 GW; b. An average output power ≥ 10 W; or c. A pulsed energy ≥ 0.1 J. • Pulse-excited Q-switched lasers with a pulse duration ≥ 1 ns having any of the following: a. An output peak power ≥ 100 MW; b. An average output power ≥ 10 W; or c. A pulsed energy ≥ 1 J. • Continuously excited lasers with either: a. A peak power ≥ 10 kW; b. An average output power ≥ 30 W. 2. Having a fundamental output wavelength > 800 nm and < 1,500 nm, as follows: • Pulse-excited lasers having a pulse duration < 1 ns and having any of the following: a. A peak power ≥ 5 GW; b. An average output power ≥ 10 W; or c. A pulsed energy ≥ 0.1 J. • Pulse-excited Q-Switched lasers with a pulse duration ≥ 1 ns having any of the following: a. An output peak power ≥ 100 MW; b. An average output power ≥ 2 W; or c. A pulsed energy ≥ 0.1 J. • Pulse-excited non-Q-switched, single TEM00 mode or having a measured beam quality M2 < 2.0 (M2 id defined in ISO 11146) with either of the following: a. A peak power ≥ 500 kW, or b. An average output power ≥ 150 W. • Pulse-excited non-Q-switched, multiple transverse mode lasers with either of the following: a. A peak power ≥ 1.5 MW; or b. An average output power ≥ 500 W. (Continued)

Critical Technology Parameter(s) (Cont'd)	• Continuously excited, single TEM00 mode or having a measured beam quality M2 < 2.0 and having either: a. A peak power ≥ 500 kW; or b. An average or continuous wave output power ≥ 150 W. • Continuously excited, multiple transverse mode lasers with either of the following: a. A peak power ≥ 1.5 MW; or b. An average or continuous wave output power ≥ 500 W. 3. Having a wavelength ≥ 1,500 nm as follows: • Q-switched lasers having: a. An output energy ≥ 0.1 J per pulse; b. A pulsed "peak power" ≥ 10 W; or c. An average power ≥ 5 W. • Non-Q-switched lasers having: a. An output energy ≥ 2 J per pulse, or b. A pulsed "peak power" ≥ 5 W, or c. An average or continuous wave output power ≥ 5 W. Some examples of the solid-state rare-earth doped lasers include Nd:YVO_4 Nd:YAG, Nd:$LiYF_4$, Nd:Y_2O_3, Yb:YAG, Cr:YAG, Er:YAG, Tm:YAG, Ho:YAG, Ho:$LiYF_4$, Yb: Glass; Yb:Er:Glass, Yb:Er:YAG, Ho:Tm:YAG, Ho:Tm:$LiYF_4$, Nd:Glass. *Note:* Non-tunable lasers include those that have discrete bands with lasers transitions that overlap, which appears to be continuous tunability but which are discrete broad lines. Erbium and Thulium have this property over the 2,750–2,900-nm range and over the 1,950–2,021-nm range, respectively.
Critical Materials	There are many issues associated with materials and the purity of materials used in lasers hosts and dopants. The key issues are listed as follows: • Homogeneous lasers host crystal materials. • Inhomogeneous composite "fusion bonded" host materials. • Low absorption lasers host crystal materials. • Higher thermal conductivity host materials. • The rare earth elements also must be extremely pure. • Ceramic YAG material. Note: The Nd, Cr, Er, Tm and other rare earth dopants provide various quality and perturbation changes in the hosts, in addition to changing the wavelength, and character of the lasing transitions in crystals and ceramic host materials. Their presence can cause a variance in dispersion, refractive indexes, coloring, ultraviolet absorption and changes in the photosensitivity, etc. Therefore, the crystalline growth process is extremely important in the homogeneity of the final lasers material. The following are some of the rare earth elements used as dopants in solid-state lasers. The primary lasers dopants along with their respective primary lasers wavelengths are shown: Lanthanum La 57, Cerium Ce 58, Praseodymium Pr 59 (1,017 nm), Neodymium Nd 60 (914–1,064–1,094–1,350 nm), Nd:$LiYF_4$, Nd:Y_2O_3, Prometheum Pm 61, Samarium Sm62, Europeum Eu 63, Gadolinium Gd 64, Terbium Tb 65, Dysprosium Dy 66, Holmium Ho 67 (2000–2100–2200 nm), Erbium Er 68 (1300–1650, 2750–2940 nm), Thulium Tm 69(1920–2030), Ytterbium Yb 70 (1025–1030–1100 nm), Lutetium Lu 71, Scandium Sc 21, Yttrium Y 39, Thorium Th 90. Chromium, Cr (1350–1600 nm).

Unique Test, Production, Inspection Equipment	• Production. • Ultrahigh purity crystalline host materials are required. • Controlled stoichiometry of the dopant and host material is crucial. • Testing: None identified. • Inspection: None identified.
Unique Software	None identified.
Major Commercial Applications	• Ytterbium and ytterbium: erbium fiber lasers are the enabling technology underlying modern fiber optic telecommunications. • Materials processing (cutting, drilling, welding, marking, heat treating, etc.). • Semiconductor fabrication (wafer cutting, trimming). • The graphic arts (high-end printing and copying). • Medical and surgical, Lasik eye surgery. • Rangefinders and other types of measurement. • Scientific research, spectroscopy, and chemical analysis. • Entertainment—laser light shows. • Decommissioning and dismantling of old nuclear facilities. • Scientific applications include DIAL/LIDAR measurements, optical spectroscopy, combustion analysis and bio-fluorescence.
Affordability Issues	• Lower overall cost due to the improved efficiency and automation processes. • Reduction in size and complexity. • More efficient cooling systems.
Export Control References	WA ML12; WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

The solid-state laser uses a solid crystalline or glassy material as the lasing host medium and is usually optically pumped. Solid-state lasers should not be confused with semiconductor or diode lasers, which are also solid state but are almost always electrically pumped (though optical pumping has been utilized with some diode lasers, such as GaSb. GaSb Type I and Type II superlattices are used for both detectors and emitters and multiple quantum well structures, where electrical current confinement is more difficult than with GaAlAs and InAsP diodes). Solid-state lasers can have the form of laser rods (cylinders) or slabs, which are pumped on the face of the material for efficiency and enhanced cooling, or thin disks which are face pumped at an angle. The thin disk laser (sometimes called thin disc laser or active mirror laser) is a special kind of diode-pumped high power solid-state laser. The main difference to conventional rod (cylinder) lasers or slab lasers is the geometry of the gain medium: the laser crystal is a thin disk, where the thickness is considerably smaller than the laser beam diameter, so that the generated heat is extracted dominantly through one end face, i.e., in the longitudinal rather than in the transverse direction. The cooled end face has a dielectric coating which is reflecting both the laser radiation and the pump radiation.

The highest power lasers (with the highest peak power) in the world are solid-state lasers. The high cost of the diode laser pumps is perceived to be the major obstacle to commercial acceptance.

The majority of modern solid-state lasers use neodymium-doped materials such as Nd:YAG (yttrium aluminum garnet which chemically is $Y_3Al_5O_{12}$). Nd:YVO_4 is also used, along with Nd:glass, and other host and doping materials, with the excitation provided by flash lamps and arc lamps. Most of these lasers have a much lower lasing threshold than ruby as well as other desirable physical and optical properties. The highest output power laser for neodymium-doped material is around 1,064 nm—in the near IR and totally invisible. The exact wavelength of the strongest lasing lines depends on the actual host material but usually doesn't vary that much. In addition to Nd:YAG and Nd:YVO_4 at 1,064 nm, some examples that lase at slightly shorter wavelengths include Nd:LSB at

1,062 nm, and Nd:YLF at 1,053 nm. But the lasing wavelengths of some host materials like Nd:$LiNbO_3$ (neodymium-doped lithium niobate) are at 1,084 nm and 1,092 nm. In some applications, the quasi-three-level neodymium transition is used to provide a wavelength of 910–960 nm, which can be frequency doubled to provide blue and cyan (455–480 nm) colors for displays and printing. New types of frequency-doubler crystals such as GdYCOB (gadolinium yttrium calcium oxy-borate) make the best of these new lasers worthy competitors to argon ion lasers for displays and printing.

Other materials include holmium-doped YAG (Ho:YAG) and Ho:YLF. These lase at around 2,060 nm and 2,100 nm, respectively. Er:YAG lases at 1630 nm, as well as at 2,840 nm. Many other IR wavelength solid-state lasers are in the development stages.

MCTL DATA SHEET 11.1-2. SEMICONDUCTOR LASER DIODES, DIODE BARS, AND LASER DIODE ARRAYS

Critical Technology Parameter(s)	Note that manufacturers typically specify the guaranteed *laser power* of semiconductor lasers at 1/3 to 2/3 of the catastrophic optical damage power level. The specification listed below is the *typical specified commercial power level,* which is guaranteed by the manufacturer. 1. Semiconductor lasers (also known as laser diodes) and laser diode arrays with wavelength < 1,400 nm and having any of the following: • Individual lasers diodes (single emitters) or any MOPA laser diode technology having a TEM00 single mode or having a measured beam quality M^2 < 2.0 (M^2 is defined in ISO 11146) and having either: a. Average or continuous wave power output levels > 1 W; or b. A peak power > 2 W. • Laser diode bars (linear/monolithic arrays) having either: a. An average or continuous wave output power > 60 W /cm of bar length; or b. A peak pulsed power > 120 W/cm of bar length. • Laser diode arrays (two-dimensional array) having any of the following: a. An average or continuous wave output power > 350 W/cm^2; or b. A peak pulsed power > 2,500 W/ cm^2; or c. An array with an average or continuous wave output total power > 5 kW • All lasers diode arrays having an output power > 150 W/cm^2 and a spatially coherent output with M^2 < 2.0. 2. Semiconductor lasers (also known as laser diodes) and laser diode arrays with wavelength ≥ 1400 nm and ≤ 2000 nm having any of the following: • Individual laser diodes (single emitters) or any MOPA laser diode technology having a TEM00 single mode or having a beam quality M^2 < 2.0 having either: a. An average or CW power output levels > 100 mW; or b. A peak power > 250 mW. • Laser diode bars, (linear/monolithic arrays) having either: a. An average or CW output power > 10 W /cm of bar length; or b. A peak pulsed power > 20 W/cm of bar length. • Laser diode arrays (two-dimensional array) having any of the following: a. An average or CW output power > 50 W/cm^2; b. A peak pulsed power > 500 W/ cm^2; or c. An array with an average or CW output total power > 500 W. • All laser diode arrays having output power > 15 W/cm^2 and a spatially coherent output with a beam quality M^2 < 2.0. 3. Semiconductor lasers (also known as laser diodes) with wavelengths > 2,000 nm and with output power > 1.0 W.
Critical Materials	• Low absorption material. • Solder alloys that thoroughly wet the surfaces avoiding voids. • Advanced Quantum Well structures (new laser materials). • High purity (99.99+%) AlGaAs, InGaAs, InGaN, InP, InAs, InAlGaAs, InGaAsP, ZnSSe, PbSSe, PbTe, AlGaAsSb, InGaSb, GaP, GaSb, GaN/AlN family of materials. • Optical coating technology for lasers diode reflective surfaces that will withstand the high temperatures required to bond the bars.

Unique Test, Production, Inspection Equipment	• Production: - Void-free soldering/mounting techniques for bars; - Low oxygen atmosphere for annealing; and - Chemical vapor deposition, MOCVD and molecular beam epitaxy technologies need improvements to produce higher yield material and higher quality of laser materials. • Testing: M^2 (beam quality) measurements to within less than 1% of diffraction-limited quality and spatial distribution measurements of arrays.
Unique Software	None identified.
Major Commercial Applications	This technology can be applied to a number of biophotonic applications as well as industrial and surveillance areas. It has found a home in many industrial applications due to its extremely small size and outstanding efficiency. • Medical - Cauterizing wounds; - Surgical cutting; - Hair removal (kills hair follicles); or - In vitro surgery. • Industrial - Pump sources—solid-state lasers for: Welders, Metalization and hardening, Laser marking/cutting/scribing, Direct diode array metalization and hardening, Scanner sources and CD/DVD players, Printer drum optical writing, and Telecom. • Surveillance - Night light source illuminators for police and security guards.
Affordability Issues	• Lower overall cost and higher efficiency than other optical pump sources. • Process and procedure improvements for high yield production using robotic assembly technology. • Mass production has made the lasers bars a cost-effective source for CD and DVD players and CD writers now robotic technology is required to provide cost-effective diode arrays. • If automation process technology is achieved with high reliability, then cost savings will allow mass production of lasers diode arrays, resulting in significant cost reduction.
Export Control References	WA Cat 6A; CCL Cat 6A.

BACKGROUND

The laser diode is a key component in modern space communication systems, fiber optics transmission systems, sensor systems, office electro-optical equipment, and certain consumer products. It has become an integral part of microelectronics, with ever-expanding applications. High-power laser diodes are used to pump solid-state lasers with high efficiency. In addition, laser diode arrays have been used to illuminate the battlefield for night surveillance. Many laser diode arrays are currently used in surveillance applications, such as in the Air Force Gunship program and on the IR illumination pod on the F-16.

Combinations of high-power laser diodes yielding greater than 1 kW continuous wave output levels are now used for materials processing. Optical packaging of multiple diodes and arrays provides total power greater than 100 W. Fiber-coupled arrays are suited to soldering, thermal processing, plastics welding, printing, ophthalmology and surgical procedures. Laser diode systems are also used for marking, cutting and other material processing applications, and provide full technical support. As a result, high-power laser diode arrays are in high demand for both commercial and military applications.

Continuous wave laser diode arrays are designed for reliability and long life at high power outputs. Laser diode bar/array powers scale from 40 W to 120 W for single bars to over 50 kW for arrays of bars. Diode arrays were originally developed for pumping of solid-state lasers but have found applications in medical and surveillance systems. Potential applications have broadened to include surface treatment, IR illumination, and particle imaging

These arrays can be used as replacements for solid-state laser flash lamps. They offer better electrical efficiency and require less cooling. The output wavelength can be controlled to closely match the pumping requirement. The beam quality, particularly of end-pumped configurations, has improved greatly.

Lifetime of laser diodes under normal conditions is approximately 10^9 pulses (cycles). Lifetime is a function of a variety of variables, including pulse width, peak power and operating temperature. However, lifetime will also vary with specific application and the input voltage/current levels. Packaging varies from water-cooled units to uncooled arrays assembled in metal-glass hermetically sealed cylindrical packages.

MCTL DATA SHEET 11.1-3. TUNABLE SOLID-STATE LASERS

Tunable solid-state lasers are defined as lasers that can be continuously tuned in laser frequency over a broad spectral range.

Critical Technology Parameter(s)	Tunable solid-state lasers having any of the following: • Output energy exceeding 500 mJ per pulse; or • An average or continuous wave output power exceeding 50 W.
Critical Materials	• Homogeneous (stoichiometric) host materials, such as alexandrite (Cr: $BeAl_2$ O_4), titanium-sapphire (Ti: Al_2O_3) and Cr:$LiSrAlF_6$ (Cr: LiSAF) materials. • Uniform doping levels within the host material is also a critical materials issue.
Unique Test, Production, Inspection Equipment	• Production: Uniformity of material, high degree of homogeneity, i.e., good stoichiometry within the material. • Testing: None identified. • Inspection: None identified.
Unique Software	None identified.
Major Commercial Applications	• Illumination sources for spectroscopic studies. • Frequency agile communications.
Affordability Issues	• Lower cost is of great concern with most crystal laser hosts. • Problematic issues of the Ti: Sapphire laser system are high cost, low reliability, short wavelength, and low energy in a chirped pulse. • High cost and low reliability results from the same reason that it is difficult to grow high-quality crystal host material—especially synthetic sapphire.
Export Control References	WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

Tunable lasers are those that typically lase by an ionic (atomic) level to a vibronic transition. This type of laser is considered broadband and tunable in a continuous way, compared with some lasers that can lase over a number of transitions within a broadband of vibration-rotational transitions. The latter type of lasers are not continuously tunable and therefore do not fall in this category.

MCTL DATA SHEET 11.1-4. CARBON DIOXIDE (CO_2) LASERS

A CO_2 laser is a gas laser in which the CO_2 molecule is vibrationally excited, either electrically or optically.

Critical Technology Parameter(s)	Carbon dioxide lasers (with wavelengths in the laser output wavelength region from 9.2 μm to 10.7 μm) having any of the following: • A continuous wave or average output power exceeding 15 kW. • A pulsed output having a "pulse duration" exceeding 10 μs and having either of the following: 1. An average output power exceeding 10 kW; or 2. A pulsed "peak power" exceeding 100 kW. • A pulsed output having a "pulse duration" equal to or less than 10 μs and having either of the following: 1. A pulse energy exceeding 5 J per pulse; or 2. An average output power exceeding 2.5 kW.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	• Welding, metal cutting, scribing, and engraving. • Suit cutting, plastic and glass molding, shaping and annealing. • Labeling and bar code engraving. • CO_2 laser radar. • CO_2 Doppler systems for navigational aids.
Affordability Issues	• Lower overall cost for welding and metal cutting sources is required by industry.
Export Control References	WA ML 12; WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

During the relaxation stage of the vibrational-rotational transitions of the excited CO_2 molecule in a CO_2 laser, given a set of mirrors for increased gain, laser radiation can be produced. Interest in CO_2 lasers stems from their continuous power capability, relatively high efficiency and ease of construction. Figure 11.1-2 shows a typical CO_2 laser system. Three gases (CO_2, N_2, and He) at appropriate concentrations are mixed and fed into one end of a discharge tube at a pressure of a few torr. The gas flows down the end of the tube in about 1 second and is pumped out the far end with a mechanical fore pump. An electrical discharge is maintained between the metallic end flanges of the tube. The ballast resistance is required because of the negative dynamic resistance of the discharge. With a fully reflecting mirror on the left and a partially transmitting mirror on the right, the device becomes a laser, which radiates in the far IR at 10.6 μm.

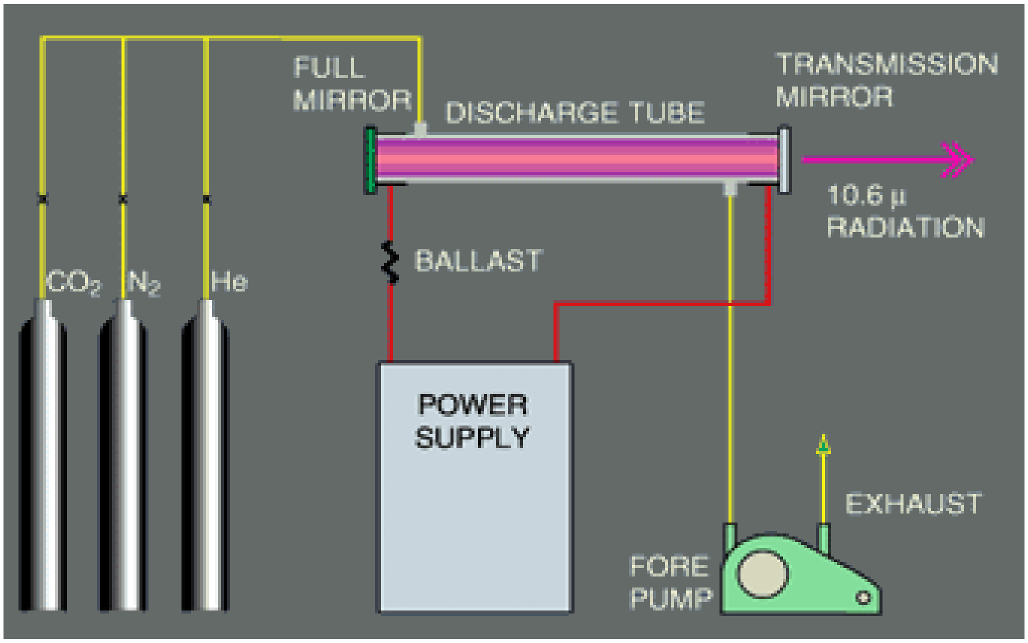


Figure 11.1-2. CO_2 Laser System with Gas Flow Discharge System

The possibility of using molecular vibrations for laser action was clearly pointed out by Poyanyi in 1961. More recently, Patel has described in some detail the laser action on the vibrational-rotational transitions of CO_2 in an electrical discharge. Shortly afterwards, progress towards high power and efficiency was achieved by Patel with the addition of N_2 and the addition of He. Other molecular systems have been made to lase, but so far CO_2 is one of the most important power producer.

Many parameters affect the design and operation of the CO_2 laser. The gas discharge can be powered with DC, AC, radio frequency, repetitive pulses, gas dynamic combustion, or any combination thereof. The mirrors can be fixed, rotated for Q-switching, or vibrated for reactive Q-switching.

The parameters that affect such optimization for flowing gas systems are:

- Electrical discharge control and current density;
- Gas mixture, pressure, and flow speed;
- Optical mode control, wavelength control, and output coupling; and
- Tube length, diameter and wall temperature.

Since the first lasers were developed in the 1960s, many uses in plastic surgery and dermatology in the treatment of cutaneous and superficial lesions have been found. Lasers are now the choice of treatment for many pathological conditions, for which no reliable or effective modality was previously available. The CO_2 laser is currently the most frequently used surgical laser. This laser has a wavelength in the invisible mid-IR portion of the spectrum, at 10,600 nm.

The energy of the CO_2 laser beam is highly absorbed by water. The absorption is so efficient that 98 percent of the incident energy is absorbed within approximately 0.01-mm tissue depth at the impact point. Therefore, no significant reflection from the skin or scattering in the tissue occurs.

When living tissue is heated to a temperature of approximately 600 °C, protein denaturation (coagulation) takes place and the tissue will subsequently disintegrate. From around 1,000 °C the water in the tissue boils and evaporates (evaporation) and when heated further the remaining dry tissue components burn (carbonization).

MCTL DATA SHEET 11.1-5. CARBON MONOXIDE (CO) LASERS

Critical Technology Parameter(s)	• Power > 10 kW continuous wave or average power. • Energy > 2 kJ per pulse.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	High power CO lasers (λ = 5 μm) are preferred over the wider point spread function CO_2 lasers (λ = 10 μm) for some materials processing. For example, 5 μW CO laser radiation can be focused to a spot size that is two times smaller in diameter than the CO_2 laser, therefore some four times higher power density. It also interacts more effectively with materials such as steel, copper, etc and human tissue.
Affordability Issues	• Lower cost than CO_2 lasers. • High efficiency for metalworking, hardening and cutting.
Export Control References	WA ML 12; WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

The usefulness of the carbon monoxide (CO) laser is demonstrated by the fact that it is better than the carbon dioxide laser in efficiency. In view of the unique operational requirements of the CO laser, the newly proposed E-beam excited CO gas dynamic laser seems to be the optimum design for a high-power laser since it possesses the potential of having both the high efficiency of an electrically excited CO GDL and the high power of a thermally pumped CO GDL. There exist many lines of a CO laser that have equal or better transmittance than those of a CO_2 laser. Therefore, the CO laser is a close competitor for the CO_2 laser. Investigation of high-power CO laser physics, the interaction physics of laser radiation with matter by deep-penetration laser cutting and welding, and the quest for new laser material-processing methods at the 5-µm laser wavelength have led to continued interest in the CO laser and their specific properties at the 5-µm wavelength.

CO lasers have some commercial applications. Among them are high-speed material processing, as well as the development of autonomous cutting of thick-wall objects such as nuclear reactors, facilities that have outlived their usefulness, large-scale samples of military equipment needed to be destroyed in accordance with disarmament treaties.

MCTL DATA SHEET 11.1-6. CHEMICAL LASERS

A chemical laser uses a chemical reaction to excite the molecules in its light-amplifying medium, rather than using electricity or photolamps like many other lasers (gas, solid state, etc.).

Critical Technology Parameter(s)	Hydrogen fluoride lasers or deuterium fluoride lasers with: • A continuous wave or average power level > 10 kW average or continuous wave power; or • A pulsed energy > 2.5 kJ per pulse. Chemical transfer lasers such as oxygen iodine lasers are listed separately in Data Sheet 11.1-7.
Critical Materials	Advanced, lightweight materials; corrosive-resistant materials.
Unique Test, Production, Inspection Equipment	Production of: • High-efficiency nozzles and nozzle banks; or • Corrosive-resistant materials for cavity, nozzles, and flow region.
Unique Software	None identified.
Major Commercial Applications	• Mining, splitting rocks. • Rock drilling and vaporizing. • Metal surface hardening.
Affordability Issues	• Lower cost required for optics and coatings. • Smaller, lighter weight materials for laser housings and flow tubes.
Export Control References	WA ML 12; WA Cat 6A (controls all hydrogen fluoride and deuterium fluoride lasers); USML XII, CCL Cat 6A.

BACKGROUND

"Fuel" for a chemical laser is fed in one side, the chemical process takes place and exhaust gases come out the other side, so the core of the laser is essentially a rocket nozzle. But the goal is not to produce thrust. The burning chemicals leaving the rocket nozzle contain very excited atoms, creating a light-amplifying region which can be tapped to extract enormous amounts of light energy.

Hydrogen fluoride and deuterium fluoride chemical lasers use fluorine atoms, produced in a combustor and then accelerated through supersonic nozzles into the laser cavity to mix with hydrogen or deuterium gas. There, under low-temperature, low-pressure conditions, the fluorine atoms mix and react with H_2 or D_2 to form HF* or DF* (an asterisk is used to denote an excited state). Stimulated emission of photons from these excited molecules by a suitable optical resonator produces 2.7-μm and 3.8-μm radiation from HF* or DF*, respectively.

The most exothermic chemical reaction known—the reaction producing the most energy per molecule—is the reaction between fluorine and hydrogen to produce hydrogen fluoride gas. A relatively small hydrogen fluoride laser can produce a lot of power. Perhaps even more importantly, hydrogen fluoride lasers can be scaled up to very large sizes and power levels. Whereas most other kinds of lasers encounter problems with overheating when scaled to larger power levels, chemical lasers are constantly exhausting spent fuel and taking in fresh, cool fuel and oxidizer, thus avoiding most overheating problems.

MCTL DATA SHEET 11.1-7. COIL, AGIL, AND OTHER CHEMICAL TRANSFER LASERS

Chemical transfer lasers receive their excitation energy by means of non-radiative transfer such as collisional mechanisms following a chemical reaction.

Critical Technology Parameter(s)	• Output power > 20 kW continuous wave or average power. • Output energy > 2 kJ of energy per pulse.
Critical Materials	• Purity of gases. • Nozzle tip alloys. • Fuels and fuel-handling materials. • Surface passivated and fluorine compatible. • Low-loss materials for optics.
Unique Test, Production, Inspection Equipment	• Production – Oxygenation technology equipment; or – Corrosive-resistant materials for cavity and flow regions. • Testing: – Laser diagnostics for 20 kW levels of power; or – Beam quality measurement equipment. • Inspection: None identified.
Unique Software	• Computer design and operational codes. • Code development for beam-target interaction effects. • Nonlinear correction components for high-energy-level beams. • Aerodynamic and solid window design codes.
Major Commercial Applications	• Remote sensing; materials processing tasks of high-speed cutting, welding, fabrication and drilling, rock crushing; and nuclear warhead/power plant dismantlement. • COIL could be used (for cutting and welding) in many other industrial applications, including shipbuilding, automotive manufacturing, and heavy machinery manufacturing. • A remote, flexible fiber-cutting tool could be used underwater to seal small leaks in hulls without expensive dry-docking. • COIL offers potential for natural gas drilling applications. The same precision, as was required for an ABL tactical weapon, can be applied to drilling and completing gas wells at depths of more than 15,000 feet. This could eliminate problems with well control, side-tracks, and directional drilling. One distinct advantage of a COIL is its potential for coupling into fiber optics with low absorption at 1.3 μm.
Affordability Issues	• Lower cost required for optics and coatings. • Smaller, lighter weight materials for laser housings and flow tubes and nozzle banks. • By enhancing the performance and lowering the operating costs of the COIL, researchers and scientists have helped to bring the O_2I device close to commercial application.
Export Control References	WA ML 12; WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

The two prime examples of chemical transfer lasers are the Chemical Oxygen Iodine Laser (COIL) and the all gas phase chemical iodine laser (AGIL). The COIL uses the reaction of chlorine gas with liquid basic hydrogen peroxide or other oxidizers to produce electronically excited gas-phase oxygen molecules. The oxygen then transfers its energy to iodine atoms, which emit radiation at 1.315 μm.

The excited iodine reaction can also be produced by mixing nitrogen chloride gas with iodine gas in a two-gas design for another iodine chemical transfer laser called AGIL, which also emits radiation at 1.315 μm. Research scientists developed the all gas-phase iodine laser (AGIL) to eliminate the heavy, aqueous-based COIL chemistry. AGIL combines the excellent laser properties exhibited by COIL (single wavelength at 1.3 μm) with lighter weight, all-gas phase reagents typically associated with an HF device. AGIL mixes chlorine atoms (Cl) and gaseous hydrogen azide (HN_3) to produce an excited nitrogen chloride (NCl) molecule. Excited NCl molecules exchange energy with atomic iodine in a manner analogous with oxygen in COIL. HN_3, a chemical cousin to sodium azide, which is used as a propellant in automotive airbags, is an extremely energetic and potentially explosive, so it must be used in a very controlled manner.

MCTL DATA SHEET 11.1-8. SOLID-STATE HEAT CAPACITY LASERS

Heat capacity lasers are solid-state lasers that operate in an uncooled mode during lasing.

Critical Technology Parameter(s)	Heat capacity lasers with any of the following: • > 5 kJ/burst; • > 10 kW average power in burst mode; • > 10% wall plug efficiency; or • Beam quality: $M^2 < 3$.
Critical Materials	• High quality, homogeneous, large boule format Nd: GGG, or other crystalline neodymium host materials, in sizes greater than 10 cm × 10 cm × 1 cm. • High-efficiency laser diode array material and processing technology.
Unique Test, Production, Inspection Equipment	• Production: High-efficiency laser diode array pump sources. • Testing: None identified. • Inspection: None identified.
Unique Software	None identified.
Major Commercial Applications	Some applications include laser welding, machining, and material cutting. Other possible applications would be cleaning stone or masonry walls by means of ablation, material hardening, and nuclear waste isolation (storage) using ceramic enclosure sealing.
Affordability Issues	• Low duty cycles can use very inexpensive diode array packages. However, in applications where average power is key criteria, HCL will need many more arrays than a comparable true continuous laser. • Lighter weight (approximately half the weight of a comparable cooled device). • Highest average output energy for a given size and weight of any laser system in the kilowatt class.
Export Control References	WA ML 12.

BACKGROUND

SSHCLs refer to the mode of operating the solid-state laser rather than the laser itself. When the heat capacity limit is reached, the laser shuts off and is cooled down by conduction or convection techniques. The SSHCL is a relatively lightweight, compact high-efficiency laser system. Laser diode array pumping is usually required to achieve the high-efficiency militarily critical level parameters.

The SSHCL uses the stored energy that an optical pump source provides to the laser medium in order to produce lasing in either a pulsed or a quasi-continuous-wave mode for a short period of time (called a burst mode). When the SSHCL medium reaches a temperature limit, called its “heat capacity,” it is shut off and cooled down for another cycle of lasing.

MCTL DATA SHEET 11.1-9. RARE-EARTH-DOPED CLAD FIBER AND PHOTONIC CRYSTAL LASERS

Critical Technology Parameter(s)	• Single transverse mode with an average or continuous wave output power > 100 W, or a peak power > 1.5 MW. • Coherent arrays of fiber lasers with an average or continuous wave output power > 200 W or a peak power > 2 MW. • Multiple transverse modes with an average or continuous wave output power > 500 W or a peak power > 5 MW. • Incoherent arrays of fiber lasers with an average or continuous wave output power > 2 kW or a peak power > 10 MW. Notes: The values given above are for CW, Q-switched, mode-locked or normal mode lasing conditions. Multiple-clad fiber lasers means two or more cladding layers are utilized.
Critical Materials	• High-purity glass host and cladding materials. • Low-absorption, low-scattering glass host materials. • High rare-earth-dopant solubility in glass host materials. • High-thermal-conductivity host materials. • High-purity rare-earth elements. • Structured photonic crystal materials.
Unique Test, Production, Inspection Equipment	• Production: Fiber drawing tower for production of high-power optical fiber with unique geometry/properties. • Testing: None identified. • Inspection: None identified.
Unique Software	• Mode selection and control in coherent arrays.
Major Commercial Applications	• Telecommunications. • Materials processing (cutting, welding, drilling, marking, heat treating, etc.). • Graphics (high-end printing and copying). • Semiconductor fabrication.
Affordability Issues	• Low-cost, high-reliability semiconductor lasers for fiber pumping. • Domestic sources for specialty fiber. • Reduction in complexity.
Export Control References	See Nd and rare-earth doped solid-state laser section of MCTL for listings of similar lasers. This entry has never been covered explicitly.

BACKGROUND

Fiber lasers have been studied to make use of the high intensity resulting from light confinement in the fiber core. In a conventional fiber laser, the pump light is coupled through the fiber core end section. The double-clad or multiclad structure of using one cladding over another allows the output power to be increased by several orders of magnitude. The pump light is launched into an inner cladding of a double clad fiber laser rather than into the (much smaller) fiber core, in which the laser light is generated. But, a single fiber (not double clad) can hardly exceed of a few tens of watts in practice, so double clad fiber lasers and other varieties of fiber lasers such as those involving air channels called photonic crystal lasers are the laser host of choice.

A new concept called "fiber embedded fiber laser" or "free shape laser" increases the potential output power, making kilowatt fiber lasers a reality. Other cladding designs using multiple cladding or multiple cores are also promising kilowatt power levels in very compact designs. Air-silica microstructure fibers (ASMF), also called photonic crystal or holey fibers, are currently the subject of intense research. Such fibers consist of a pure silica core surrounded by a regular array of air holes, which leads to exceptional guiding properties, as waveguides which can not be obtained in conventional step-index fibers. The combination of these fiber designs with Yb-doped cores results in unique properties for high power lasers. This is due to the quantum defect of ytterbium, leading to high efficiency and low thermal load. In general, fiber based laser systems are immune against any detrimental thermo-optical problems due to their special geometry. This fact is due to the large ratio of surface to active volume of such a fiber that ensures very good heat dissipation.

Clad fiber lasers are actually a subset of rare-earth-doped solid-state lasers. The main features distinguishing clad fiber lasers from the conventional continuous wave lasers are their high efficiency (60–70 percent), immunity to destructive thermal effects, simplicity of heat removal, and robustness of optical resonator. The fibers are contained in a glass host. They have a much different geometry than conventional solid-state lasers, which produces both advantages and disadvantages over conventional laser systems, and thus they are being treated as a different class of laser. They have a very small transverse-cross-section pump cavity surrounding an even smaller laser diameter cavity. However, the length of the fiber laser can be many meters. The small pump cavity allows very high optical conversion quantum efficiency, but requires the use of high brightness diode laser pump arrays. The high surface-to-volume ratio, and subsequent short distance for heat conduction, make thermal management much easier in fiber lasers than in conventional solid-state lasers. The small, usually single-mode, laser cavity provides excellent beam quality, but the high concentrated power can cause optical damage or nonlinear optical effects in the fiber, which keeps the power scaling limit relatively low. The limit of the output power scaling is determined by the damage threshold of the fiber endfaces and the mirrors. However, continuous wave power in excess of 100 W has been recently demonstrated with a cladding-pumped, ytterbium-doped, single-mode fiber laser and over 6 kW from a proprietary commercial double-cladding design. Higher continuous wave output powers are anticipated from fiber-based laser systems as high-power, high-brightness pump sources become available. To achieve very high powers, an array of fibers must be used. There are a number of companies that market fiber lasers from a few watts to nearly 10 kW in multimode and single-transverse-mode laser configurations.

For years, solid-state lasers have replaced traditional laser systems in numerous materials processing applications. Now, high-power fiber lasers bring the ultimate in solid-state reliability and operating convenience to such applications. Fiber lasers are a great leap forward in laser technology. Fiber lasers are more easily integrated into industrial processes in comparison to conventional lasers due to:

- Exceptionally high reliability;
- High repetition rate;
- High-quality focusable beam;
- Nearly maintenance-free operation;
- No water cooling;
- Optimized pulse duration;
- Single-mode fiber delivery line; and
- Standard wall-plug operation and high electrical efficiency.

MCTL DATA SHEET 11.1-10. FREE ELECTRON LASERS

A free electron laser can be generated by passing an electron beam through a sinusoidally varying magnetic field, which generates tunable, coherent, high-power radiation.

Critical Technology Parameter(s)	• Free Electron lasers (at any wavelength) with power levels > 10 kW average power. Note that average power is based on the total energy divided by the burst time when pulse durations are shorter than a second.
Critical Materials	Homogeneous material and field strength for wiggler magnets.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Medical applications are the primary commercial use for free electron laser lasers.
Affordability Issues	Lower cost.
Export Control References	WA Cat 6A; CCL Cat 6A.

BACKGROUND

Free-electron lasers currently span wavelengths from millimeter to visible and potentially ultraviolet to X-ray. They can have the optical properties characteristic of conventional lasers such as high spatial coherence and a near-diffraction-limited radiation beam. They differ from conventional lasers in using a relativistic electron beam as a lasing medium, as opposed to bound atomic or molecular states, hence the term free-electron.

MCTL DATA SHEET 11.1-11. FREQUENCY CONVERTED LASERS

A frequency-converted laser is a laser in which a nonlinear optical process, such as optical harmonic generation, optical parametric oscillation, stimulated Raman scattering, or stimulated Brillouin scattering, is used to convert the laser wavelength from that of the primary laser to another other wavelength.

Critical Technology Parameter(s)	• Lambda < 360 nm, and an average power exceeding 150 W. • 360 nm < Lambda < 1,400 nm, and an average power exceeding 50 W. • Lambdạ > 1,400 nm with an average power exceeding 1 W. Lambda is the wavelength of the frequency-converted laser.
Critical Materials	• Certain combinations of primary solid-state laser media and nonlinear optical crystals allow efficient frequency conversion by optical harmonic generation to visible wavelengths or optical parametric oscillation at mid-wave infrared wavelengths. These may or not be controlled materials by current export controls [only the following crystals are explicitly export-controlled under the Wassenaar Arrangement (6.C.), potassium titanyl arsenate, silver gallium selenide ($AgGaSe_2$), thallium arsenic selenide (TAS, or Tl_3AsSe_3) and zinc germanium phosphate]. • Engineered materials, such as optically poled lithium niobate, or potassium titanyl arsenate may allow conversion (harmonic or parametric) by a different mechanism than the angle-tuned “phase matching” traditionally employed. Considerable R&D is ongoing to fabricate new types of such materials with broader transparency ranges and enhanced damage resistance. Such “engineered” materials are controlled by current export controls only if their performance exceeds limits given by section 6.C.4.d. of the International Dual-Use List or the corresponding section of the CCL. • Fiber Raman lasers incorporating Raman resonators in the fiber and using Bragg grating reflectors written into the fiber of the Raman converter are capable of efficient, sequential Raman conversion to longer wavelengths. (Fiber Raman converters are only controlled if they employ an export-controlled pump laser by current export controls.)
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Fiber Raman converters are a key technology for high-power, long-haul optical telecommunications that allow conversion of the output from powerful ytterbium fiber lasers from 1,080-nm to the 1,450–1,500-nm spectral region needed for telecommunications. Frequency conversion of neodymium lasers operating on the 900-nm, 1,060-nm, and 1,300-nm bands to the red, green and blue regions of the visible spectrum is central to many solid-state lasers used for industrial applications in printing and in recording of electronic media, in marking, cutting and scribing of materials, as well as medical (opthalmic) applications and entertainment applications (laser displays and laser light shows). Infrared conversion using parametric oscillators allows conversion of near-IR 1,060 nm solid-state lasers to the mid- and far-Infrared regions as tunable sources for research applications in chemical analysis and pollutant monitoring. Applications to real-time industrial process control to reduce harmful emissions and by-products have been reported at the evaluation level. Infrared conversion also offers an attractive pathway to providing eye-safe optical laser radar sources for detection of clear-air turbulence, and for early detection of obstacles to aerial navigation such as power lines. A number of tests of such systems have been reported, and one such system has been installed at a commercial U.S. airport for Federal Aviation Administration evaluation.

Affordability Issues	None identified.
Export Control References	WA ML 12; WA Cat 6C; USML XII; CCL Cat 6C.

BACKGROUND

In many crystalline solids, the indices of refraction are different for different polarizations of the electric field of the light. If one picked the right crystal and the right orientation, a harmonic signal of one polarization would have the same index as a fundamental wave of a different polarization. This would mean that the two waves would propagate together in phase through the crystal, and power could be transferred from the fundamental to the other wave. In relatively short order, substantial amounts (~30 percent) of power conversion was demonstrated using crystals for which this situation obtained, such as potassium di-hydrogen phosphate (KDP); its isomorph, potassium di-deuterium phosphate (KDP); and ammonium di-hydrogen phosphate (ADP). Similar phase-matching "bookkeeping" could be used for the inverse process, optical parametric oscillation, in which a signal wave generates two longer wavelength waves at the so-called signal and idler frequencies. In addition, other processes, such as "sum frequency generation" and "difference frequency generation," could be set up and demonstrated.

There is another class of frequency-conversion processes developed during the past 40 years in which a light field is coherently scattered from sound waves in a material (Brillouin scattering), or from molecular or atomic modes in solids or gases (Raman scattering). In such a process the scattered wave is frequency shifted by the amount of the mode from which it is scattered.

SECTION 11.2—OPTICS

Highlights

- Micro-optics have begun complementing and replacing electronic components on chips, reducing heat and improving speed and throughput while reducing cost.
- Lightweight technology for space optics, vital to our space requirements, are being addressed with new high-strength composite technology.
- MOEMS chips are now replacing many opto-electronic components, which reduces the heat load and improves the speed and throughput while reducing costs of standard procedures. These chips significantly reduce the weight of the overall system.
- Conformal optics improve aerodynamic flow significantly, reduce signature, and reduce weight for nose cones and missile domes. However, they require strong aspheric corrections. Compared with the traditional hemispheric dome, a conformal ogive (bullet-shaped) missile dome can reduce drag by up to 50 percent. The overall design is accomplished by new computer-controlled algorithms.
- Reducing the weight of military optics—vital to our transport and space requirements—is addressed in numerous new light-weighting technology developments, especially with the application of high-strength, low-mass composites and silicon carbide components.
- Computer-supported integrated design, fabrication, test, and assembly methods permit the transition of hybrid optical devices into the fully integrated optical systems required for miniaturization and high performance in future military products.
- Real-time, computer-controlled optical grinding and polishing, along with micropolishing, has cut the time required to fabricate aspheric optics and conformal optics by a factor of 10 or more.
- Lightweight, high-stiffness precision optical components are now being built with an “areal density” (surface density) of less than 10 kg per square meter. Some prototypes have now demonstrated less than 5 kg per square meter.
- Optical “composites” and foam components having a coefficient of linear thermal expansion less than 5×10^{-6} are now being incorporated in transportable optics and under development for military applications.

OVERVIEW

This section includes technologies ranging from night-vision optics and lightweighted optics to improved process technology for aspheric lenses, reflectors, and conformal optics. It covers the broad discipline area of optics and optical component technologies, which are of critical military utility. Optics are quite relevant to the discipline and applications of many critical military systems, and in many cases, some of these technologies address complementary commercial systems. The optical technologies in this section include new development, refinement, and production processes for metal, ceramic, and dielectric optical substrates and for new optical composite materials. Materials that support optics and optical substrates include ceramics, low-thermal-expansion glass, metals, and optical composites. Optical materials will be covered in a companion section. Optical systems technologies will be presented here if they are generic in nature. If they are unique to another technology area, they will only be referenced here and covered in that specific technology section of the MCTL. An example would be certain space optics (e.g., deployable optics) which will be covered in the Space Systems Technology section.

Various optics technologies are covered in this section. Some are contained within the main technology data sheet. One of these is lightweight optics for high-sensitivity hyperspectral surveillance imaging systems. Another is optics-manufacturing technology, especially that of aspherics and conformal optics, which is a major concern to the military. Aspheric and conformal optics technologies are also covered in this section.

Cooled optics are critical to the military for high energy laser (HEL) applications. Passively cooled optics that use carbon filaments for conductive/radiative cooling, and which were developed for space applications, are now being used in terrestrial applications are also addressed.

BACKGROUND

Optics have become the pervasive enabler for a significant number of disciplines and applications that support both military and commercial systems such as surveillance, telecommunications, physical security, laser weapons, and, more recently, data storage and optical computing. Now micro-optics are broadening the base of this enabling technology discipline by extending optics into the micro and even the nano world.

Just as the development of fiber optics enabled the information technology area, micro-optics will continue to have a major enabling influence on the development of other new technical areas. Optics are now having an impact on the nanosciences (e.g., MOEMS sensors) where optically fabricated devices are able to sense, evaluate, communicate, and act.

Specific Types of Optics

- **Optical mirrors.** As used here, the generic phrase “optical mirrors” covers conventional optics formats. This category includes laser optics and surveillance optics (that are not unique to space), dielectric reflector optics, and composite and metal optical mirrors. The militarily critical parameters for optics include surface finish characteristics, laser damage criteria, and high-stiffness, lightweight technology including high removal coring technology, spin casting technology, and optical composite technology.

  A relatively new mirror technology—that of silicon carbide material—is currently a leading material in the development of military optical systems that require lightweight, high-stiffness optics. Many optical “composites” and special metallic foam components are also beginning to play a significant role in military systems.

- **Deformable/AO.** A significant technological development during the past 30 years in the field of laser optics is AO, which was developed to negate the optical path variance caused by fluctuations in air temperature density variations and the atmospheric motion and turbulence that consequently scatters a laser’s beam. AO relies on a deformable mirror, sometimes called a “rubber mirror,” to compensate for tilt and phase distortions in the atmosphere. Deformable optics are also referred to as smart optics, active optics, or AO. The mirror typically has hundreds of actuators that change hundreds to thousands of times per second, enabling the mirror to modify the laser beam so that it can travel further through turbulent air.

- **Conformal-Aspheric Optics.** Conformal-aspheric optics reduce the drag on missiles and other nose cones and therefore are desired for greater range and better stability of the missile. Nontraditional freeform (conformal) optics are unique because they conform to the aerodynamic requirements and reduced-signature mechanical shapes of the platform on which they are integrated or mounted. Conformal optics are optical components that have nontraditional optical surface shapes that conform to the mechanical configuration imposed by the constraints of the system into which the optics are integrated or mounted.

- **MOEMS.** MOEMS, the optical version of MEMS, are created using micro-machining and lithography techniques. MOEMS incorporate optics as one or more of the components on the chip and are typically of the same scale as silicon ICs, shrinking the size of their predecessor macro devices by an order of magnitude or more. MOEMS sensor devices can sense environmental parameters and manipulate or report information. Typical MOEMS have functions including: pressure sensors, accelerometers, pumps, chemical sensors, light manipulators, Adaptive Optics, optical switches, and biochips for sensing pathogens and toxins.

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.2. OPTICS

CHANGES FROM LAST MCTL

Additions:

Production process technology for high homogeneity optical and technical glasses (Data Sheet 11.2-5) was added to the list.

MCTL DATA SHEET 11.2-1. OPTICAL MIRRORS

Critical Technology Parameter(s)	• Lightweight, high stiffness precision mirror structures with an areal density (surface density) of < 10 kg per square meter. • Lightweighted optical mirrors with an areal density < 10% of a solid optical component (same dimensions and same material). • Mirrors with stiffness to weight ratio ≥ 5 X that of steel. • Optical “composite,” fiber or foam mirror components having a coefficient of linear thermal expansion < 5×10^{-6} in any coordinate axis and an areal density of < 15 kg per square meter. • Aspheric mirrors with optical apertures > 50 cm, with surface roughness < 2 nm and a coefficient of linear thermal expansion of < 3×10^{-6} /°C at 25 °C. • Actively cooled mirror optics > 10 cm in diameter (or major axis) which use liquid or gas cooling technology with channels embedded under the faceplate at a depth < 25×10^{-3} inches below the face plate. • Passively or actively cooled mirror optics > 10 cm in diameter (or major axis) which use carbon filaments to provide conductive/radiative cooling. • Silicon Carbide mirrors > 20 cm in diameter (or length of major axis). • Beam steering mirrors > 10 cm in diameter (or length of major axis) that maintain a flatness of lambda/4 or better (for lambda = 633 nm) and having a control bandwidth > 200 Hz.
Critical Materials	• Lightweight, high-stiffness, precision structures with an areal density of < 10 kg per square meter. • Composites with very high stiffness to weight ratios that have a coefficient of thermal expansion of < 3×10^{-6} /°C at 25 °C. • High stiffness to weight ratio material composites ≥ 5X that of steel. • Specialized, and in some cases exotic, materials are required for composite optics. • Carbon filamentary cooling channels for optics.
Unique Test, Production, Inspection Equipment	• Production: None identified. • Testing: precision metrology associated with the fabrication and certification of optics and the in situ characterization and profiling of the surface during operations. • Inspection: None identified.
Unique Software	None identified.
Major Commercial Applications	Optical mirrors are used in all lasers. The critical technologies listed here are directly applicable in commercial versions of very high-energy laser beam welders and metal cutting lasers. Lightweighted optics and aspheric optics are currently used in some astronomical telescopes. • Aspheric Optics are used in many commercial field telescope designs. • Lightweighted mirrors are finding homes in numerous applications from laser welders to space surveillance optics. • Silicon carbide optics are just now entering the commercial market and have replaced surveillance optics in a number of cases. • Beam-steering mirrors are used in astronomical instruments to slew and track objects of interest. • Composite optics have replaced glass optics in airborne and mobile observation platforms due to the lightweighted configuration.

Affordability Issues	The affordability issue of lightweighted optics is indirectly addressed by the fact that the overall system weighs less, affording the luxury of reducing a lot of other support and control hardware. High stiffness to weight provides good optical tolerance conditions while yielding mass that in turn minimizes the support structure mass. Lower overall mass results in less costly transport and support costs. • Reduction in weight saves costs to deploy into space or carry on a military vehicle. • Lightweighting permits higher slew rates with less torque required in steering components.
Export Control References	WA Cat 6A; CCL Cat 6A.

BACKGROUND

Optics are critical components in many military weapons systems ranging from night vision optics to the most complicated precision guided munitions. There are many other applications in between these including sensing, targeting, communications, and reconnaissance optical systems.

Lightweighted and Composite Optics has been a growing field for both commercial and military systems since the military first began significant developments in this area some 40 years ago. The development of novel lightweight optics and support structures is of vital importance to the advancement of both ground and space-based astronomy. Primary mirrors are one of the main drivers of the mass of space-based optical systems, as the other spacecraft masses are roughly proportional to the optical system mass. Therefore, lightweight optics are an essential component of reducing launch costs while increasing payload utility.

The requirement for lightweight mirrors for both space and airborne applications has often been met through the use of beryllium or low-expansion glass-like materials. The current availability of silicon carbide substrates and the development of suitable manufacturing and finishing process, however, provide an alternative material for such uses.

Silicon carbide mirrors are a recent addition to the lightweight mirror family of structures. The high stiffness-to-density ratio of silicon carbide allows mirrors of very low weight to be designed and still maintain the necessary surface figure to provide the performance required for high-resolution optical imaging.

MCTL DATA SHEET 11.2-2. DEFORMABLE OPTICS/ADAPTIVE OPTICS (ACTIVE OPTICS)

Deformable optics includes any optical component whose optical surface can be controlled or adjusted dynamically to implement a given surface figure or to enhance the optical system performance.

Critical Technology Parameter(s)	Any continuous or multielement optical mirror or mirror component(s) surface, and specially designed components which: 1. Dynamically positions mirror surfaces at > 300 Hz: a. Surface positioning accuracy < 50 nm; or b. A repositioning actuator accuracy and/or precision of < 20 nm. 2. Provides correction stability of a given optical figure to < 30 nm RMS, for vibrations and impulses < 1 g.
Critical Materials	• Improved piezoelectric actuators with less hysteresis and higher piezo coefficients. • Improved bonding techniques for actuators to face plates. • Higher bandwidth actuators with lower voltages. • Improved nulling techniques for the control surface. • Increased bandwidth electronic components and actuators.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Astronomers need ground-based optical telescopes. They are crucial tools for the understanding of the Universe, but their image quality is severely limited by the (quasi-static) errors in the telescope itself and the (very dynamic) atmospheric turbulence inside and over the telescope. Active optics are used to overcome the first limitation and deformable/adaptive optics the latter, producing images with resolution near the diffraction limit of the optical system. There are a number of physical limitations to adaptive optics performance, leading to successive generations of more and more sophisticated techniques detailed below. One important example employs systems of deformable mirrors and wavefront sensors to correct for optical disturbances in the atmosphere through which large ground-based telescopes peer. Other possible application areas include commercial laser beam correction, laser beam forming, laser materials processing, scanning optical systems, optical probes and confocal microscopes, coupling of micro-optics, and several areas of optical imaging, including imaging of the retina in vivo.
Affordability Issues	Lower cost will result with further development work, which should improve performance, decrease complexity and increase the bandwidth substantially. This will reduce the cost for the next generation of giant telescopes.
Export Control References	WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

A significant technological development in the field of laser optics is deformable or adaptive optics. Deformable optics are also referred to as “smart optics,” “adaptive optics,” or “active optics.” These terms are sometimes interchanged in publications and discussions.

It should be noted that (quasi-static) errors in optics such as telescope optics are usually controlled by a low-bandwidth optical system referred to as “active optics.” The (high dynamic) controlled optics typically required for correcting atmospheric turbulence inside and above the telescope are usually referred to as “adaptive optics,” and in the case of a closed-loop system, they are sometimes referred to as “smart optics.” However, the terms are quite often interchanged.

Developed to combat fluctuations in air temperature and the consequent atmospheric turbulence that modifies the phase distribution and scatters the laser’s beam, adaptive optics rely on deformable mirrors to compensate for the tilt and phase distortions in the atmosphere. The mirror typically has hundreds of actuators that change hundreds to thousands of times per second when driven by a wavefront sensor, enabling the mirror to modify the laser beam so that it can travel further through turbulent air. This technique of deforming optical surfaces has succeeded in producing even sharper and clearer images from terrestrial telescopes than the Hubble Space Telescope. This is primarily due to the fact that once phase corrections are minimized, the greater light gathering power and the larger apertures of terrestrial telescopes provide increased resolution.

The most distinctive components of an adaptive optics system are the deformable mirror itself, which actually makes the optical corrections in reflection, and the wave-front sensor which measures the turbulence at a few Hertz to thousands of Hertz. These two key systems function, which in concert under the control of a high-speed computer, can provide significant improvements to image quality and resolution. But many other components, such as the actuators, processors, and control electronics, are required to complete the system.

Today, deformable mirrors for astronomy are usually made of a very thin sheet of glass or low-thermal-expansion material with a diameter of several inches to meters in size. Attached to the back of the glass are various kinds of actuator devices that expand or contract in length in response to a voltage signal, bending the thin sheet of glass locally to the intended wavefront correction. A deformable mirror is able to correct a distorted beam of light from a star by straightening out the incoming wavefront.

The second key component of the adaptive optics system is a wave-front monitoring sensor. For astronomy and military applications, these sensors must measure turbulence hundreds to thousands of times a second. The detector doing this work is typically a fast CCD, similar to those used at slower speeds in today’s video cameras, or else a set of avalanche photodiodes mapping out the centroid of beamlets in a Shack-Hartmann setup.

The arrangement of optics in front of the detector varies, depending on the wavefront sensing scheme being used. The two main schemes used for astronomy today are curvature sensing and Shack-Hartmann wavefront sensing. Light from a natural guide star or reflected by a laser guide star is incident on the wavefront sensor. The light is focused by a two-dimensional array of tiny lenslets onto a fast CCD camera. In the absence of atmospheric turbulence, a “perfect” wavefront from a distant star would be flat and could be focused to a point by the telescope optics. The wavefront sensor’s lensets would focus this light to an evenly spaced checkerboard array of spots on the CCD camera. Turbulence introduces variable distortions to the wavefront, which cause the array of spots on the CCD detector to be irregularly spaced and to dance around rapidly on the detector as the turbulence in the air changes with time. Using rapid measurements of the exact position of all the spots on the CCD detector, the computer can reconstruct the shape of the incident wave front, and hence can derive what signals need to be sent to the deformable mirror to make the wave front flat again.

The control system is generally a specialized computer that calculates from the wave-front-sensor measurements the commands sent to the actuators of the deformable mirror. The calculation must be done fast (within 0.5 to 1 ms); otherwise, the state of the atmosphere may have changed, rendering the wavefront correction inaccurate. The required computing power needed can exceed several hundred million operations for each set of commands sent to a deformable mirror. As in active optics systems, zonal or modal control methods are used. In zonal control, each zone or segment of the mirror is controlled independently by wave-front signals that are measured for the subaperture (usually on the order of 10 cm) corresponding to that atmospheric zone. In modal control, the wave-front is expressed as the linear combination of modes that best fit the atmospheric perturbations.

MCTL DATA SHEET 11.2-3. CONFORMAL OPTICS

Conformal optics are optical components that have nontraditional optical surface shapes that conform to the mechanical configuration imposed by aerodynamic, stealth, or other requirements of the platform (i.e., missile, aircraft, etc.) into which the optics are integrated or mounted.

Critical Technology Parameter(s)	• Free-form conformal technology which is designed to provide: a. Optical surfaces to < 30 nm accuracy, b. Surface roughness < 10 nm rms. c. Nose cone surface figures that reduces drag by > 30% from conventional hemispheric domes; or d. Spatial frequency conformal optics grinding residuals < 1 nm in width. • Complex optics including: concave conic sections, aspheric toroids, far off-axis optical segments, and aspheric surfaces with departures > 600 waves from the best-fit sphere, including when the surfaces are rotationally axisymmetric.
Critical Materials	Critical materials range form the UV, visible, to the IR for missile dome applications where high strength and transmission are traded off with manufacturability.
Unique Test, Production, Inspection Equipment	Production: • Unique grinding and polishing equipment that produces free-form optical surfaces to submicron form accuracy, < 1.0 nm (visible) to 10 nm (IR) rms surface roughness, and eliminates mid-spatial frequency grinding residuals require further development. Inspection and Testing: • Unique profilometer and interferometer configurations suitable for inspecting and testing free-form optical surface shapes to less than 50 nm is required.
Unique Software	• Programming software to support five-axis CNC freeform machining to the level of accuracy required is not fully developed. • Software to support on-machine inspection and feedback automation is not fully developed. • Software to support the development metrology instrumentation.
Major Commercial Applications	Military-unique applications drive the importance of this technology. Commercial requirements will emerge when it is demonstrated that an affordable manufacturing technology is available to the commercial sector. The current commercial application is for aircraft windows. Boeing concluded that there is a definite role for conformal optics on low-signature aircraft based on reduced drag and improved flow patterns. There is also strong interest in illumination systems optics, as well as scanner and microlithography applications using conformal designs.
Affordability Issues	The extreme accuracy, unusual shapes, and difficult-to-work materials place the majority of freeform optical shapes required well beyond current fabrication capabilities—at any affordable cost.
Export Control References	None identified.

BACKGROUND

Conformal optics lower external observability, improve aerodynamic flow, reduce friction, reduce signature, and reduce weight. Compared with the traditional hemispheric dome, a conformal ogive (bullet shaped) missile dome can reduce drag by up to 50 percent. Benefits include major reductions in aerodynamic drag (by as much as 50 percent), reduced time to targets (by as much as 60 percent), and reduced platform and weapon signatures.

Trade-offs can be made between rocket motor sizes, range, decreased propellant, warhead, missile size, and other variables. Nontraditional optical shapes can also optimize an electro-optical sensor's field-of-regard to increase weapon system effectiveness. This crosscutting manufacturing technology is broadly applicable to all military services.

MCTL DATA SHEET 11.2-4. MICRO-OPTO-ELECTRO-MECHANICAL SYSTEMS (MOEMS)

MOEMS are created using micro-machining and etching techniques along with optical elements in combination with MEMS technology.

Critical Technology Parameter(s)	• All MOEMS specifically designed for military applications such as phase correctors for HEL systems, beam path conditioning and monitoring, and sensing toxic elements, pathogens or chemical warfare agents. • MOEM deformable mirrors with > 100 actuators and a displacement throw of > 2 μm. • MOEM deformable mirrors with repeatability < 10 nm for > 99% of the actuators. • MOEMS with a closed loop bandwidth > 1 kHz and an open loop bandwidth > 5 kHz.
Critical Materials	• None identified.
Unique Test, Production, Inspection Equipment	• Production: Very stringent tolerances are required for micro-opto devices and components. Micro lenses and micro-beam splitters require position tolerances of < 1 mrad but often exceed 10 mrads. • Testing: None identified. • Inspection: None identified.
Unique Software	None identified.
Major Commercial Applications	MOEMS are used in a wide range of applications for medical, biotechnology, automotive, wireless telecommunications, fiber-optic telecommunications, information peripherals, environmental monitoring, industrial automation, aerospace, and defense, including: • Sorting of solids, liquids and gases based on spectroscopy (e.g., for environmental monitoring, waste management or food quality control); • Development of miniature medical sensors and recorders for permanent implantation in patients; • Mass data storage devices; • Systems for storing densities of terabytes per square centimeter; • Integrated micro-opto-mechanical components for identify-friend-or-foe systems; • Displays and fiber-optic switches/modulators; • Active, conformable surfaces for distributed aerodynamic control of aircraft; • Adaptive optics; or • Sensing and monitoring.
Affordability Issues	The lower cost comes about since MOEMS can be fabricated with current technology on silicon substrates. Mass production can achieve tremendous cost savings, and the small size provides utility in new and diverse applications.
Export Control References	None identified.

BACKGROUND

MEMS technology, which evolved from the semiconductor fabrication industry, is rather mature in some applications. MOEMS are typically of the same scale as silicon integrated circuits, shrinking the size of their predecessor macro devices by one or two orders of magnitude or more. These novel optical elements are characterized by their high efficiency, design flexibility, lightweight, small size, and ruggedness. Furthermore, they can be replicated at low cost in mass production. These properties give MOEMS the potential to become key components in many future optical and electro-optical systems.

The primary goal of any MOEMS program is to develop the technology so as to merge sensing with actuation and computation to realize new systems that bring enhanced levels of perception, control, and performance to military and commercial systems. MOEMS programs focus on projects whose primary goal is to endow systems with the ability to alter or modulate the path of a light beam and, in some cases, to temporally or spectrally modify the light beam itself. The most common micro-optical elements are those that reflect, diffract, or refract light.

MOEMS devices can sense and/or manipulate the environment and/or elements of the environment. Typical MOEMS (and some MEMS) have several functions, including pressure sensing for both radiation and chemicals, acceleration, pumping, light manipulation, and bio-chip procedures. MOEMS are now being designed for use in a wide range of applications, including medical, biotechnology, automotive, wireless telecommunications, fiber-optic telecommunications, information peripherals, environmental monitoring, industrial automation, aerospace, and defense. The small size and high integration level of MEMS and MOEMS reduce the cost for the function they perform and increase reliability, compared with predecessor macro sensor and actuator designs.

Fabrication of micro-optical components is already feeding dynamic markets with a large variety of products that are more or less on the verge of inexpensive mass production. Two major application areas for MOEMS are telecommunications and data communications, while miniature optical sensors (e.g., spectrometers and interferometers) have a growing part in many kinds of biotechnological, chemical and pharmaceutical applications. There are developments in optical microstructures for a range of items, such as low-cost fiber-optic components, polymer waveguide elements, fiber switches, mass-producible microlenses made of thermoplastics or glass, microstructured photonic bandgap materials, and optical sensor tips for investigating nanostructures.

Micro-opto-electromechanical systems (MOEMS) are transforming the field of adaptive optics by providing compact, inexpensive, high-speed micromachined deformable mirrors. Such mirrors will be used as wavefront correctors in imaging and beam-forming systems that are affected by optical path aberrations. Some of the key applications for which MOEMS deformable mirrors are currently being tested include astronomical telescopes, ophthalmic surgery, retinal imaging, point-to-point laser communication, and UV lithography.

MCTL DATA SHEET 11.2-5. PRODUCTION PROCESS TECHNOLOGY FOR HIGH HOMOGENEITY OPTICAL AND TECHNICAL GLASSES

Critical Technology Parameter(s)	This process control technology covers the production of high homogeneity optical and technical glasses with the following critical parameter levels. The critical technology for producing these glasses involves a melting process capable of producing homogeneity in the range of 2 ppm or better. • Homogeneity better than or equal to $\pm 2 \times 10^{-6}$. • Bubble Class "B0" or better ("0" = zero)* * See Reference 1b for definition of Bubble Class "B0" or "0".
Critical Materials	Material issues directly associated with the selection and the purity of the materials used in high homogeneity glasses are important; the key ones are. a. Very High purity batching materials; and b. High purity refractory and precious metals used as molten glass contact materials.
Unique Test, Production, Inspection Equipment	The manufacturing of high homogeneous material is performed by using critical process controls, innovative processing equipment, and high performance test and high resolution inspection methodology as well as handling equipment including: a. Specialized Furnace geometry; b. Multiple energy input technology; c. Automated control system; d. Automated delivery and forming technology; e. Sophisticated process and thermally control of annealing equipment with high resolution Δ T capability; f. High Laser energy damage testing for particulates (inclusions); and g. Large format interferometry and metrology equipment.
Unique Software	Unique critical software has been developed for control of key system parameters (used in process control of the furnace, refractory, and annealing ovens).
Major Commercial Applications	Primary commercial applications include: laser gain materials (laser hosts); precision imaging optics; laser gyroscope optics; athermal optical windows; laser protection materials; high energy beam delivery system optics; polarizing beam splitters; lightweight optics of many types; waveguide laser devices; IR imaging and detection systems; radiation shielding; solarization resistant materials
Affordability Issues	The key issues that relate to affordability are: a. Economies of scale; b. Commonality across applications and systems; c. Precious metals availability and cost; d. Energy cost; and e. Batch material availability and cost.
Export Control References	This production process technology is controlled under 6E002 in the CCL.

BACKGROUND

The production of high purity, high homogeneity optical/technical glasses and glass ceramics is based upon a process that has been developed and optimized for over 130 years. A strategic, uninterrupted domestic supply of high quality glasses and glass-ceramics initially was in high demand by the U.S. military for optics and optical surveillance applications. As a result, critical processes and production technologies were developed.

Over the past three decades the demand for higher performance optical materials has increased exponentially. This is due to the mass commercialization of optics for consumer, industrial, medical, and military applications. Many night vision optics for both man (helmet displays) and machine (gunship night scopes) require high quality, high homogeneity optical glasses. Transmissive surveillance optics components also require high purity, low bubble content, high homogeneity optical materials. The demand for high homogeneity optical material has also increased because of the prevalence of electronics and lasers within optical systems and the common acceptance of opto-electronics and micro-opto-electro-mechanical systems (MOEMS). To meet these demands higher performance and higher homogeneity optical materials are continually needed. The central factor in these materials is the control of the deviation of the refractive index (homogeneity). Among optical glasses the minimum homogeneity level of consideration for critical military applications is called “H3” or “C” by various sources, which is a variance of less than two parts per million (2 ppm) and the highest homogeneity level currently achievable in production is identified as H5 or “AA” (0.5 ppm).

SECTION 11.3—OPTICAL MATERIALS

Highlights

- Robust optical materials protect sensors from hazardous atmospheric conditions while allowing desired radiation to reach the sensors.
- Durable thin film optical coatings reduce reflection and scatter and selectively filter incoming radiation to sensors, resulting in enhanced sensor performance.
- Superior optical materials provide improved media for lasing (production of intense, monochromatic, coherent light beams) for rangefinding, laser radar, and IR countermeasures applications.
- Nonlinear optical materials can shift the frequency of incident radiation to more desirable frequency values with higher intensities for targeted applications.
- Nonlinear optical materials can reverse the propagation direction and phase variation of a beam of light. This is important for imaging through atmospheric turbulence and for correcting laser beam aberrations.
- Optoelectronic materials convert photons into electrical signals useful for imaging applications.
- Solar cell materials convert photons into electrical signals useful for space power applications.
- Optical materials used in fiber optics transfer information faster and at higher bandwidths than electrical wires.

OVERVIEW

This section includes optical materials and optical materials technologies for linear and nonlinear materials with transmission in the ultraviolet, visible, or IR spectral regimes. Bulk materials as well as thin films and coatings are covered. Depending on the application, these materials and/or coatings may be required to cover either broad or narrow frequency bands and perhaps be “frequency agile” (have the ability to shift their frequency as a function of internal or external stimuli). Special emphasis is placed on materials and coatings that are affordable, maintainable, and durable in harsh environments experienced in military operations, such as exposure to high speed rain and dust, high temperatures, and high structural loads associated with high speed, maneuvering flight.

In most cases, the mission requirements of individual weapons platforms and their associated optical systems dictate the specific capability of the optical materials and coatings in the components. Capability refers to not only the technical or scientific performance accuracy of the system or sensor component, but also includes the ability to withstand the mission environment, durability, availability, and cost of ownership.

Because of factors such as the much higher level of sensitivity required and the severity of the environment in military operations versus those of commercial applications, many of these products and technologies are not expected to be strong candidates for dual-use applications. For example, a major performance requirement in military systems is protection from rain and dust erosion on exposed optical surfaces, which becomes a factor at speeds greater than 350 to 400 mph, whereas the auto industry’s needs are limited to speeds of less than about 100 mph. Other factors involving electro-optical countermeasures are peculiar to the military. Some possible dual-use examples are: (1) some of the nonlinear optical materials will likely be used to produce laser radiation at appropriate wavelengths which can be used for detection and identification of chemical species in environmental pollutants; and (2) some less costly, less sophisticated forms of optics coating technology could be adapted by the automobile and commercial aviation industries for night vision (infrared) sensors.

BACKGROUND

Quality optical materials are essential for the successful completion of many military missions. The following provides a useful way for organizing materials according to their characteristics and functions in applications:

Optical elements. Optical elements include devices such as lenses, prisms, beamsplitters, mirrors, polarization components, and filters used to modify a beam of light. Lens elements are used in many applications, such as telescopes, collimators, magnifiers, and optical transceivers. They are used to converge, diverge, or collimate incident light. Prisms are used in optical systems to deflect a light beam. They can invert or rotate an image, disperse light into its component wavelengths, and be used to separate polarization states. Beamsplitters are used to separate a light beam into two separate paths. Filters are used to attenuate light intensity at desired wavelengths, by absorption of radiation in the filter material or by utilizing the interference properties of optical thin film coatings applied to a substrate. Some metallic absorbing films are particularly insensitive to wavelength. On the other hand, the amount of absorption by colored glass filters can vary by as much as several orders of magnitude in only tens of nanometers.

The materials used for all these elements must be of high optical quality and uniformity and must be capable of maintaining their optical properties at very high power densities for many applications. Thermal characteristics can be particularly important in applications in which the part is subjected to high temperatures, or must undergo large temperature cycles. Mechanical characteristics of a material affect how easy it is to fabricate the material into shape, which affects product cost. Scratch resistance is important if the part will require frequent cleaning. Shock and vibration resistance are critical for military applications. The chemical characteristics of a material, such as acid or stain resistance, can affect fabrication and durability.

Window materials. Window materials are used to isolate two physical environments while allowing light to pass. Window materials serve to protect delicate sensors from harsh external operating environments. Therefore, such materials must match high optical transparency with high mechanical and thermal strength. Examples of situations that require window materials are vacuum or space-based sensors and seeker windows in high-speed missile sensors.

Optical thin-film coatings. Many optical components are coated with thin layers of material(s) that are different from the substrates. These optical thin-film coatings are used to modify the reflection and transmission properties at the surface of the optical element. Thin-film coatings can reduce reflections at lens surfaces, allowing more light to reach the sensors behind the lens, and can also block unwanted wavelengths of light. These films can range from simple (a few layers) to quite complex (over 100 layers) depending on the range of conditions (wavelength and angle of incidence, for example) over which the reflection/transmission ratio must be optimized. Applications for thin-film coatings include spectral radiometry, calorimetry, and color separation in cameras. They can also be used to protect an optical element made of a soft window material from scratching, staining, or other physical damage.

Adhesives. Optically clear, high-strength adhesives are used for connecting optical components and for providing heat and moisture resistance.

Support for optical elements. Beryllium is replacing glass in some large-aperture space and ground telescopes used in high-resolution military systems. It is also desired in the nose cones of missile interceptors and in lightweight optical subsystems for satellite sensors because of its lightweight, excellent thermal properties for rapid cooling, and extremely high specific stiffness. Graphite composite is also lightweight and has high dimensional stability. It is useful for the supporting structures of optical elements.

Opto-electronic materials. Detector materials for IR, visible, and ultraviolet wavelengths convert optical energy into electrical signals that can be transmitted, analyzed, and processed electronically before being presented to a user as imaging or targeting data. A variety of opto-electronic materials are used to convert the photons emitted or reflected by a target into useful electronic signals. Semiconductors such as Ge, GaAs, and HgCdTe are sensitive to IR and visible wavelengths, and photomultipliers are useful for visible and ultraviolet detection. Thermistor materials, such as VO, sense thermal radiation with decreases in electrical resistance. Electro-optical sensors are discussed in MCTL Section 11.4.

Semiconductor optical materials for space based solar cells. Photovoltaic solar cells are constructed from crystalline semiconductor optical materials. The band gap of the semiconductor is engineered to match the energy available in the sunlight so that a percentage of the incident light is converted into electrical energy. Devices made of multiple stacked semiconductor materials with different tailored band gaps achieve increased efficiency compared to single band gap material. The state of the art space solar cells available today are triple junction III-V material semiconductor cells. Industrial processes for producing semiconductor material of high quality (material composition and crystalline structure) for solar cell applications are well advanced since they use the same processes the semiconductor industry uses for making integrated circuits and other electrical devices. Solar cells' lightweight and reliability make them useful as power sources for military satellites, communications satellites, and scientific space probes. The materials used in space based solar cells must be resistant to radiation damage; this feature is not required for earth-based solar cells, which are not exposed to intense radiation environments.

Laser materials (Gain media). Lasers produce intense beams of radiation that are monochromatic, coherent, and highly collimated. Lasers wavelengths are limited to discrete resonant transitions in the lasing media, and can be tuned only over narrow frequency bands.

Lasers include a gain medium in which radiation can be amplified, an excitation source (e.g., a power supply, optical flashlamps), and most include a resonator structure (mirrors aligned to confine the radiation and to repeatedly feed it back into the gain medium to be amplified via the stimulated emission process). The gain medium can be gas, liquid, or solid (e.g., solid crystalline rods, Argon gas, semiconductors, etc.). In general, the gain medium and excitation source for a laser are chosen to suit a variety of specifications, such as desired wavelength, power output, power consumption, duration and frequency of the pulse cycle, and durability. The gain media addressed in this section of the MCTL will be confined to solids.

Solid crystals of high-strength, optically transparent material with good thermal properties, such as sapphire or yttrium aluminum garnet (YAG), are doped with metal atoms, such as chromium, neodymium, or erbium, to produce laser rod materials for use as lasing media. These rods can be shaped and polished to yield high-power, solid-state lasers that have applications for rangefinding, laser radar, and IR countermeasures.

Semiconductor optical materials for diode lasers and vertical cavity surface emitting lasers (VCSELS) are in wide use for commercial and military products. These materials will be discussed in Section 11.1, Lasers.

Frequency conversion materials. The use of nonlinear optics to adapt lasers to wavelength-specific applications has created a need for new, efficient, easily grown, and damage-resistant nonlinear optical materials. Well-developed materials, such as Nd:YAG, exist for frequency conversion of lasers, but materials having higher conversion efficiencies are desired.

- A material is nonlinear if the transmission, reflection, or refraction of light in that material depends on the intensity of the light. (The materials used for the applications discussed previously in this section have all been linear media and thus not subject to this effect.) Nonlinearity arises in some materials because of the large electric fields associated with laser radiation. High fields distort the arrangement of electrons in the atoms of a material and change its index of refraction (velocity at which light propagates in the material). This nonlinearity is typically only observed at very high light intensities such as those provided by pulsed lasers, and only in certain classes of crystals and other types of materials such as organics. Nonlinear optical properties of materials give rise to a variety of useful effects.
- The nonlinear response can allow the exchange of energy between electromagnetic fields of different frequencies. *Sum frequency generation* is the mixing of two incident light waves of frequencies ω_1 and ω_2 in a nonlinear medium to create radiation of frequency $\omega_3=\omega_1+\omega_2$. *Second-harmonic generation* (SHG), also called frequency doubling, is a special case of sum frequency generation. Photons interacting with a nonlinear material are effectively "combined" to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons.
- Sum frequency and second-harmonic generation are standard techniques to produce a new coherent output from existing laser systems and especially to access the short wavelength range towards the ultraviolet region of the spectrum.

- In *Difference frequency generation* (DFG), the interaction of photons at frequencies ω_1 and ω_2 incident in a nonlinear material generates a new photon at frequency ω_3 where $\omega_3 = \omega_1 - \omega_2$ (where $\omega_1 > \omega_2$). The field at ω_1 is often an intense pump field supplied by laser radiation, while the field at ω_2 is a weak signal field. Difference-frequency generation yields amplification of the ω_2 field, along with generation of another field at frequency ω_3, called the idler field. This phenomenon is called *parametric amplification*.
- A device that exploits this process is called an *optical parametric oscillator (OPO).* An OPO converts the power output of a pump laser to a coherent output at the signal and idler frequencies that can be tuned continuously over large frequency ranges. The radiation produced is shifted toward lower energies (longer wavelengths) from the original pumping laser's radiation. Unlike a laser, an OPO does not depend on resonant transitions and can thus produce wavelengths that are difficult or impossible to obtain with a laser. OPOs can also be tuned over wide frequency ranges, unlike lasers.
- Optical materials with strongly nonlinear behavior at IR frequencies, including potassium titanyl phosphate, BaB_2O_4 (BBO crystal), and $AgGaS_2$, are useful for parametric amplifiers. Parametric amplification of laser energy has diverse applications, including IR spectroscopy for biological/chemical agent detection, inertial confinement fusion, high-brightness laser-plasma X-ray, and electron and proton sources.

Optical Phase Conjugation is an optical process occurring in a nonlinear medium to exactly reverse the propagation direction and phase variation of a beam of light. With a phase conjugate optical element, the image is not deformed when passing through an aberrating element twice, as it would be when passing through a conventional non-ideal optical element. Optical phase conjugation is important for correcting laser beam aberrations to near diffraction-limited beam quality, for combining a laser array into a single coherent beam and for imaging through atmospheric turbulence.

Eye and sensor protection materials. Selectively transparent materials capable of statically or dynamically protecting soldiers' eyes and sensitive detector elements from high-power laser radiation on the battlefield can be constructed from a variety of materials. Passive bulk filter materials and selectively fabricated thin-film coatings can block known laser wavelengths, and active filter materials, such as nonlinear optical materials or nematic or cholesteric liquid crystals, can block all wavelengths that exceed a specified power density.

Obstructive materials. Absorbing or scattering materials can be used to obscure valuable targets and confuse or jam enemy sensor arrays. Obstructive materials can include fog-oil or smoke particles that have diameters close to the wavelength of visible light or other materials, such as graphite flakes and brass powders, tailored to scatter or absorb specific IR wavelengths.

Fiber optics designed for short-wave IR, mid-wave infrared, and long-wave infrared laser transmission. Optical fibers are waveguides make of transparent dielectric optical materials whose function is to guide visible and infrared light over long distances. Long distance optical communication by glass fibers is already a well-established commercial technology. However, this occurs in the visible and near IR regions of the spectrum. Specialized glass and hollow-core fiber-optic materials have been developed for the transmission of laser energy at IR wavelengths where standard fiber-optic materials are not transparent. Chalcogenide and heavy metal fluoride glasses, sapphire crystals, and hollow glass waveguide structures have been used to carry IR laser energy over short distances; however, losses remain high for long-distance (greater than 1 m) transmission. IR fiber optics has uses for laser power delivery, thermal imaging, radiometery, and chemical sensors.

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.3. OPTICAL MATERIALS

CHANGES FROM LAST MCTL

Additions:

One new technology (fiber laser material) was added to the list.

Deletions:

Data Sheet entitled Fixed Laser Line Protection Materials for Eyes and Sensors.

Changes:

- Three technologies, as follows:
  - IR Window and Dome Materials;
  - IR Coating Materials for Protection Against Hazardous Environments; and
  - Germanium Optics.

Combined to form MCTL Data Sheet 11.3-1, Infrared (IR) Windows, Domes, and Protective Coatings.

- Two technologies, as follows:
  - Optical Sensor Materials, Electro-Optical Sensors (Materials for Cooled Arrays—Scanning and Staring); and
  - Optical Sensor Materials, Electro-Optical Sensors (Materials for Uncooled Arrays—Staring).

Combined to form MCTL Data Sheet 11.3-5, Optical Sensor Materials, Electro-Optical Sensors (Materials for Cooled and Uncooled Arrays).

- Three technologies, as follows:
  - Laser Materials (Solid-State, Tunable Lasers);
  - Sintered Ceramics; and
  - Fiber Laser Materials.

Combined to form MCTL Data Sheet 11.3-6, Laser Materials (Solid-State Tunable Laser Materials, Sintered Ceramics, and Fiber Lasers Materials).

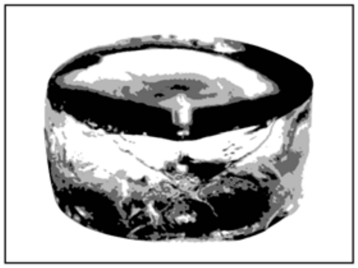
MCTL DATA SHEET 11.3-1. INFRARED (IR) WINDOWS, DOMES, AND PROTECTIVE COATINGS

This technology protects sensors from harsh environments while transmitting useful radiation to the sensor.

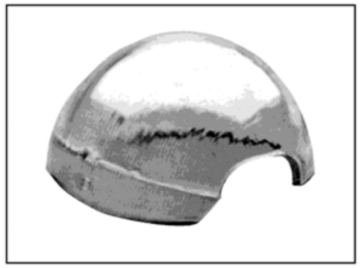
Critical Technology Parameter(s)	• Transparent over any portion of the 1–12 μm spectral band. • Strength > 48 MPa (7 ksi) for bulk material. • For window applications, plate size > 8 cm diameter with thickness > 1 cm. • For dome applications, material volumes of > ~100 cm^3. • Ability to withstand 2-mm diameter raindrop impacts at rainfall rate of 2.5 cm/hr with relative speed between raindrop and coating of > Mach 1.0. • Ability to survive aerothermal heating rate > 100 W/cm^2. • Ability to withstand blowing sand at 8 m/s wind velocity with particle density > 1.0 gm/m^3 and particle size distribution 74–350 μm. • For Germanium (Ge) material: resistivity < 15 ohm cm and absorption ≤ .03 cm^{-1} @ 10.6 μm.
Critical Materials	Window and dome materials: zinc sulfide (ZnS), zinc selenide (ZnSe), sapphire, germanium (Ge), aluminum oxynitride (ALON), silicon (Si). Thin film coatings: diamond, diamond-like carbon, magnesium fluoride, thorium fluoride and other fluoride materials, boron phosphide, gallium phosphide, Ge, ZnS, ZnSe, Si, etc. Exotic glasses with extended IR transmission, e.g., chalcogenide glasses. H_2Se gas.
Unique Test, Production, Inspection Equipment	Equipment for rapid grinding and polishing of IR window and dome materials and optical elements. Single-point diamond turning machines. Grid coating inside dome to prevent humidity effects, surface finishing processes. Magnetic rheological finishing. Equipment for measuring absolute reflectance to an accuracy of ≤ 0.1%. Automated thin film deposition and monitoring equipment.
Unique Software	Software for automated monitoring and production of bulk and thin film components.
Major Commercial Applications	IR thermal imaging for security and auto safety applications. CO_2 laser optics for cutting, welding, marking and forming materials.
Affordability Issues	In the past, affordability was not a major issue. The unique optical properties of the materials made them the choice, at any price. As commercial IR applications develop, price will be an issue, and competition from improved IR transmitting glasses for non-aerodynamic applications where strength is a lesser concern would be significant.
Export Control References	WA ML 15; WA Cat 6C; USML XII; CCL Cat 6C.

BACKGROUND

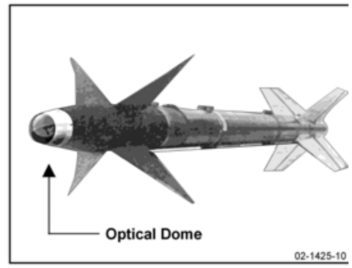
IR windows and domes for guided weapons systems are required to protect the IR sensors internal to the devices from the environment, including aerodynamic forces. In particular, high strength for thermal shock resistance and rain and sand erosion at high speeds is required for the window and dome material. Domes may either be hemispherical or flat or faceted in shape. Coatings are applied to windows and domes for abrasion resistance, and to reduce reflection and improve transmittance while rejecting unwanted wavelengths.



Raw Material



Optical Dome



Missile Mounted Dome

Germanium (Ge) is a high-refractive-index material widely used for windows and domes in IR systems operating in the 2-µm–14-µm range. The use of antireflection coatings is essential with Ge material because Ge has a high refractive index (n ~ 4; thus reflection loss for an uncoated two-surface Ge element is 53 percent at a wavelength of 10 µm). Ge is non-hygroscopic and non-toxic, has good thermal conductivity, excellent surface hardness (692 Knoop), and good strength. However, the transmission of germanium is very sensitive to temperature; it becomes opaque near 100 °C.

Sapphire offers excellent optical transmission from the ultraviolet to the mid-infrared (150 nm–6 µm). It is an extremely hard material that can be cleaned repeatedly without damage or scratches, and is chemically inert. The hardest of the oxide crystals, sapphire retains its high strength at high temperatures, has good thermal properties and excellent transparency. These properties encourage its wide use in hostile environments where optical transmission in the range from the visible to the near infrared is required.

Aluminum oxynitride (ALON) is a very durable optical ceramic with a high degree of transparency from the ultraviolet through the mid-infrared spectral region (.2–6 µm). It is equivalent to sapphire in terms of optical quality, low density, high strength, and high durability. However, its properties are isotropic, making it scaleable to very large sizes using conventional processing methods.

Zinc selenide (ZnSe) and zinc sulfide (ZnS) are preferred materials for optical windows and domes due to their low absorption at infrared wavelengths, as well as some visible transmission (.6–18-µm transmission range for ZnSe, .4–14 µm for ZnS). ZnSe is non-hygroscopic, relatively soft, scratches rather easily and has a high resistance to thermal shock. ZnS is slightly harder and more chemically resistant than ZnSe, has good resistance to thermal and mechanical shock, withstands reasonable abrasion, and is hygroscopic. Both materials require an anti-reflection coating due to their moderate refractive index (~ 2.2–2.5) if high transmission is required.

Silicon is used as an optical window primarily in the 3- to 5-µm band. It has high thermal conductivity and low density, and requires antireflection coatings for high transmission due to its high refractive index (3.5).

Commercial Significance

Current Raytheon focal plane array sensors for the Cadillac Night Vision system use IR-transmitting glass lenses to reduce cost, but other units made by FLIR Systems use ZnSe optics. Generally, commercial systems use slower (less curved) and smaller aperture IR optics because of cost reasons, plus their applications have less demanding performance requirements. There are notable differences in the relative sizes of current commercial and military markets for ZnS and ZnSe. Military and commercial markets may be similar in terms of total material volumes, but the commercial market comprises a larger quantity of small items, while the military market comprises a much smaller number of high-end items.

MCTL DATA SHEET 11.3-2. SPECIALTY TRANSPARENT MATERIALS (COATINGS AND FILTERS)

This technology provides specialty thin film materials for application to a surface of a device which affect a change in the optical properties of the device, such as reflection, transmission, refraction, and conductivity.

Critical Technology Parameter(s)	Coating layer thickness and refractive index reproducibility. The tolerances required for these parameters are highly dependent on the desired optical performance of the particular coating or filter. In general, critical performance parameters are > 99% transmission for antireflection (AR) coatings, > 99.9% reflectivity for high reflection (HR) coatings and < 0.1% scatter.
Critical Materials	Selected dielectrics, semiconductors, and polymers, e.g., TiO_2, SiO_2, Al_2O_3, ZnSe, ZnS, Ge, Si, ThF_2, MgF_2.
Unique Test, Production, Inspection Equipment	Automated thin film deposition, growth monitoring, measurement and test equipment, e.g. high vacuum systems, ellipsometers, spectrophotometers, scatterometers, interferometers, etc. This equipment also has dual uses for commercial applications.
Unique Software	Automated thin film deposition and monitoring software, software for performance characterization of coatings.
Major Commercial Applications	Telecommunications, surveillance cameras, lighting industry, astronomy, factory automation, environmental monitoring, medic.
Affordability Issues	Many of the thin film deposition processes are proprietary to a particular company. Proprietary considerations have made it difficult to launch broad initiatives to develop improved coatings. Also, per part cost may be high for small numbers of units due to lack of economies of scale.
Export Control References	WA Cat 6C; CCL Cat 6C.

BACKGROUND

Thin film filters are extremely thin layers of materials, such as dielectrics, semiconductors, and metals, that are applied to the surface of a substrate like glass, metal or germanium to effect a change in its optical properties. Effects such as reflection, refraction, antireflection and conductivity can be produced and modified by expert design of the choice of layer materials, number of layers, and their respective thickness in relation to the incident wavelengths of light. The specific spectral properties desired will dictate whether the filter will consist of a single layer of material or of multiple layers of different materials and will also dictate required material properties such as refractive index, absorption, dispersion, scatter, etc.

Optimum operation of visible and IR sensors is highly dependent on the availability of specialty transparent materials for thin film coatings and filters. The use of specially deposited optical thin films to optimize the optical properties of sensor windows and lenses has been demonstrated using many different materials systems. The goal of these thin-film coatings is to increase the transmission of desired wavelengths while rejecting undesired wavelengths.

MCTL DATA SHEET 11.3-3. NONLINEAR OPTICAL MATERIALS FOR WAVELENGTH CONVERSION

This technology involves the utilization of materials which, when placed in front of a laser beam, can shift the output to a shorter wavelength while maintaining a coherent beam.

Critical Technology Parameter(s)	Spectral bandpass at 0.2–12 μm. Average output power > 2 W. Complex coatings with high damage thresholds. Low concentrations of unwanted impurities (e.g., Na, Fe, O, K, C) are important because of the high optical power densities present. Defect scattering or absorption leads to inefficient nonlinear conversion.
Critical Materials	ZnGeP2; potassium titanyl arsenate; GaSe; RTA CdGeAs2; AgGaSe2; potassium titanyl phosphate; TAS; AgGaS2; SiNBa3; LiNbO3; Periodically poled materials. Periodically grown GaAs, ZnSe. Ga:CaYOB, a-Barium Borate (a BBO), or oxy-borate crystals, as a class.
Unique Test, Production, Inspection Equipment	X-ray diffraction to determine optical axis and phase matching angles, high voltage source for poling.
Unique Software	Nonlinear Optical Materials Code (Sandia National Labs) http://www.sandia.gov/imrl/XWEB1128/xxtal.htm
Major Commercial Applications	Optical parametric oscillators. Tunable laser systems. Flat-panel displays.
Affordability Issues	None identified.
Export Control References	WA Cat C; CCL Cat 6C.

BACKGROUND

Nonlinear optical materials can be used to transform high-power laser energy at one wavelength into a coherent beam at a shorter wavelength suitable for near-IR, visible, or ultraviolet applications. With the assistance of nonlinear optical materials, solid-state long-wavelength sources can be used to generate useful amounts of laser light at a variety of operationally useful wavelengths for display and countermeasure technology.

Nonlinear optical materials typically consist of dielectric or semiconductor crystals, such as LbNiO3 or ZnGeP2, selected for their conversion efficiency in the source wavelength region. Wavelength conversion occurs at an integer fraction of the original wavelength (typically 1/2, 1/3, or 1/4), with a conversion efficiency that depends on the incident power and the cross-sectional area of the interaction region. Guided-wave structures or resonant cavities can increase the length of the interaction region and improve conversion efficiency.

In the past decade frequency-converted lasers have gone from a few watts average power to over 100 W. Optical parametric oscillators have gone from milliwatts to tens of watts.

The commercial application of interest to the Japanese and Germans is for frequency-converted RGB lasers for laser displays, laser printing, etc. This class of laser, that is, all solid state (laser diode→microchip Nd or Yb→frequency converter, 2–5-W cw outputs, 480 nm, 530 nm, 670 nm) is widely expected to replace argon and krypton ion lasers, and most major U.S. laser manufacturers also have lasers of this type in their catalogs now.

The IR-converted lasers may find considerable application to pollutant measurement, industrial process control, etc.

Laser markets for visible and IR wavelengths only available from large, inefficient gas-discharge lasers are now wide open to efficient, compact, all-solid-state lasers incorporating frequency converters. This has been called "the reinvention of the laser," with only a modest amount of exaggeration.

MCTL DATA SHEET 11.3-4. HIGH-ENERGY LASER (HEL) OPTICAL COMPONENTS (MIRRORS, BEAMSPLITTERS, WINDOWS)

This technology provides optical components that can be manufactured with high damage resistance for transmitting or reflecting high energy laser beams.

Critical Technology Parameter(s)	Substrates diameter > 0.1 m for silicon carbide. Low water fused silica (< 100 ppm water). Optical coating with total loss < 200 ppm.
Critical Materials	Si, silicon carbide, low water fused silica coating materials, thorium fluoride, ZnSe,SiO2, TiO2, ZrO2, Nb2O5, Al2O3, CaF2, MgF2, Be, beryllium materials, sapphire, suprasil. Highly purified fluoride and chalcogenide glasses with low absorption in 2.6–2.9-μm and/or 3.6–4.0-μm region.
Unique Test, Production, Inspection Equipment	Single point diamond turning machines, coating vacuum chambers for large optics. Characterization equipment to measure absorptance (laser calorimetry), total internal scatter (TIS), bi-directional reflectance distribution function (BRDF), reflectance.
Unique Software	None identified.
Major Commercial Applications	Photolithography optics (future), space-based optics. High-power lasers for welding, forming, cutting. Research telescopes for astronomical applications.
Affordability Issues	High quality, low-cost optical components with low water content leads to rapid advances in the extreme ultraviolet photolithography market.
Export Control References	WA ML 19.

BACKGROUND

Mirrors, beamsplitters, and windows for high-energy laser applications require careful design to handle the extreme power densities associated with high-energy laser operation. Specially formulated glasses and coating materials with very low absorption, limited thermal expansion, and high damage resistance have been developed for high-energy laser optics, along with the specialized manufacturing capability to create and shape these components.

Fluoride and chalcogenide glasses along with more familiar silica and sapphire materials can be manufactured with very high purities and low residual water concentrations to minimize unwanted photon scattering and absorption within the optics. High mechanical strength is also important for resisting damage caused by laser-induced localized heating of the components during use.

An important military application for high-energy laser optical components is for precision beam control for directed-energy weapons. Future deep-ultraviolet photolithography systems and current laser-cutting applications also require high-quality components for high-energy laser optics.

Commercial Significance

The deep ultraviolet optics necessary for optical lithography have also required the development of specially purified and processed fused silica substrate materials. These efforts have all benefited from prior U.S. investments in materials purification technology for ultra-low-loss fiber optics.

MCTL DATA SHEET 11.3-5. OPTICAL SENSOR MATERIALS, ELECTRO-OPTICAL SENSORS (MATERIALS FOR COOLED AND UNCOOLED ARRAYS)

This technology involves detecting thermal (infrared) radiation emitted by an object and converting it to a visual image of the object.

Critical Technology Parameter(s)	*Cooled Material:* (1) Wafer size > 3” (HgCdTe/CdZnTe) or > 4” (InSb); (2) Threading dislocation density (by EPD) < 10^6 cm^2; or (3) External quantum efficiency > 70%. *Uncooled Material:* (1) Temperature coefficient of resistance (TCR) for bolometers > 2%/K; (2) Temperature coefficient of dielectric constant (TCD) for pyroelectrics > 1%; (3) Thermal time constant (μ) < 100 ns; or (4) Thermal conductance (G) < 10 nW/K.
Critical Materials	*Cooled*: (1) InSb; (2) HgCdTe on low defect CdZnTe substrates; CdZnTe substrates are obtained from Japan and there is no U.S. supplier. However some of the U.S. FPA contractors make these substrates for their own consumption; (3) HgCdTe on low cost silicon substrates; (4) InAlGaAs for QWIP detectors; and (5) Platinum Silicide (PtSi). *Uncooled*: (1) Barium Strontium Titanate (BST); (2) Lead Zirconate; (3) Vanadium oxide; and (4) amorphous silicon. Note: CdZnTe substrates are obtained from Japan and there are no U.S. suppliers.
Unique Test, Production, Inspection Equipment	*Cooled*: (1) Epitaxial growth equipment capable of producing a layer thickness uniform to < ± 2.5 percent across 75 mm; (2) Dry-etching equipment for high-density pixel delineation; or (3) Indium bump hybridization tools. *Uncooled*: (1) Specialized deposition systems for BST, vanadium oxide, amorphous silicon; (2) Miniaturized thermo-electric coolers for temperature stabilization; or (3) MEMS manufacturing technology.
Unique Software	None identified.
Major Commercial Applications	Surveillance, remote sensing surveys, baggage scanning devices, inspection, medical imaging, prevention maintenance, infrared astronomy, industrial quality control (filling coke bottles), energy efficiency audits, electrical power circuit inspection, firefighting.
Affordability Issues	Cost issues for cooled sensors: Defect reduction in growth process. Material yield increases. Lower cost alternative technologies (III-V QWIP, QDIP, Type II superlattice structures). Cooling may affect market value. No cooling = lower cost = greater market volume BUT uncooled = slower response times and less sensitivity. Uncooled photon detectors such as poly crystalline PbSe are another low cost alternative.
Export Control References	WA ML 15; WA Cat 6C; USML XII; CCL Cat 6C.

BACKGROUND

Optical sensor materials for detecting thermal radiation absorb infrared (IR) energy emitted by an object and convert this energy into an electrical signal. The electrical signals generated by an array of sensors can be converted into a thermal image of the targeted scene and used for navigation or target detection and identification in low-light or cluttered environments.

Sensors used for tactical thermal imaging are designed to operate in the midwavelength (MWIR 3–5 microns) and longwavelength (LWIR 8–12 microns) atmospheric windows for IR transmission. Space-borne sensors intended for missile defense applications are designed for operation at longer wavelengths, between 10–20 microns. Some applications such as satellite imaging require sensing in the near infrared (NIR ~.7–1.0 microns) and short wavelength IR (SWIR ~1–3 microns) spectral ranges as well.

Early IR images were created by scanning a line array of detectors across a scene. Each detector was individually connected to a preamplifier, and the array of preamps was multiplexed to a single output. To improve sensitivity, the number of detector elements on the focal plane sensor has been increased. This imaging design is called Time Delay and Integrate (TDI). In this case, a rectangular shaped or linear M × N array of detectors is used. Each detector in the array is mechanically and electrically coupled to an electrical processing unit cell on a Read Out Integrated Circuit (ROIC). For the case of a linear array, the number of elements in the M dimension is small. The signals for the detectors in the M dimension are selectively delayed in time to be synchronous and summed for improved signal to noise characteristics. Subsequently, the IC multiplexes the N channels.

Cooled Sensors

All cooled imaging sensors use thermoelectric or closed cycle refrigeration systems to reduce the thermal background noise from the detector and its optics, thereby increasing the signal to noise ratio of the system and improving its sensitivity. Common materials for cooled detector applications include HgCdTe, InSb, and InGaAs. HgCdTe can detect IR radiation across a wide spectral range (SWIR through VLWIR). InGaAs is for short wavelength applications only (~1 to ~2.5 microns). Recent advances with quantum-well infrared photodiode (QWIP) and quantum-dot detector structures using mature GaAs III-V materials technology have produced large-format cooled arrays with high operabilities. QWIP arrays can be easily tuned for different wavebands by changing quantum well thicknesses, with very-long wave (> 12 micron) or multicolor operation possible. InSb and Platinum silicide (PtSi), formed by ion implantation of Pt into Si, are capable of operating in the SWIR and MWIR windows only. (However, the quantum efficiency of PtSi is low (< 1%), therefore it is rarely used.) Extrinsic doping of semiconductors such as Si or Ge can be used to produce cooled detector arrays, similarly to PtSi, but these materials place more stringent demands on the cooling system.

Low-cost large format (4 Mpixel or greater) QWIP arrays are now offered by some commercial vendors with applications for commercial surveillance, remote sensing, and astronomy.

Uncooled Sensors

Optical sensor materials used for uncooled infrared detection measure the small differences in the radiant temperature of an image by measuring the corresponding change in the resistance (thermistor elements) or capacitance (pyroelectric elements) of the sensor material when it is heated by IR radiation emanating from the object of interest. Because these detector materials have thermal noise characteristics that are relatively insensitive to operating temperature, they can be operated at room temperatures without cryogenic cooling. Proper choices of material and optimized detector geometries can also enable large arrays of individual detector elements to be manufactured monolithically on single substrates. Monolithic arrays of uncooled IR detector materials permit the development of high-resolution IR imagers that are smaller and less expensive than previous cooled designs, and have many military and commercial applications.

Microbolometers (devices for detecting IR radiation) have been manufactured using a wide variety of materials, and recent work has focused on high-density arrays fabricated with standard Si CMOS processing methods. Work continues on reducing cost per pixel and reducing thermal time constants. Experimental arrays have been produced using antenna-coupled bolometers, in which a micromachined antenna is attached to the bolometer element to increase its sensitivity without increasing its thermal capacitance (thus permitting highly sensitive arrays with faster response times). Recent experiments in Australia have also focused on multispectral uncooled detectors produced by suspending bolometer elements in capacitively tuned resonance cavities above the electronic readout circuitry.

The relatively low cost of uncooled thermal detectors has allowed a number of niche commercial applications to develop. A mature commercial manufacturing base now exists for uncooled bolometer arrays. Fire fighting (viewing through smoke) and police surveillance applications benefit from the availability of uncooled thermal detectors, as do applications involving nondestructive testing and predictive maintenance.

MCTL DATA SHEET 11.3-6. LASER MATERIALS (SOLID-STATE TUNABLE LASERS, SINTERED CERAMICS, AND FIBER LASERS)

This technology encompasses various types of solid laser gain hosts, including some single wavelength materials, and others which can tune over a broader spectrum.

Critical Technology Parameter(s)	1. *Stimulated emission cross-sections:* Alexandrite ($Cr:BeAl_2O_4$) > 3 × 10^{-19} cm^{-2}; Ti:Sapphire ($Ti:Al_2O_3$) > 8 × 10^{-19} cm^{-2}; Thulium-doped garnets (Tm:YAG, Tm:YSGG) > 0.95 × 10^{-20} cm^{-2}; Cr:ZnS > 1 × 10^{-18} cm^{-2}. 2. *Thermal conductivity:* Alexandrite ($Cr:BeAl_2O_4$) > 22 W/m*K; Ti:Sapphire ($Ti:Al_2O_3$) > 52 W/m*K; Thulium-doped garnets (Tm:YAG, Tm:YSGG) > 12 W/m*K; Cr:ZnSe > 18 W/m*K; Cr:ZnS > 26 W/m*K. 3. *Thermal lensing susceptibility* (dn/dT) < 10 × 10^{-6} K^{-1} Ti:Sapphire ($Ti:Al_2O_3$) Figure of Merit (α840 nm: α514 nm) > 150 cm^{-1} (α = absorption coefficient). 4. *Impurities:* Low concentration (< ppm) of unwanted elemental impurities including C compounds. 5. *Sintered Ceramics:* Maximum unwanted impurity concentration < 1 ppm. Maximum ceramic porosity after densification < 100 ppm. Maximum grain boundary width after sintering ≤ 1 nm. Optical absorption/scattering loss < 0.0015 cm^{-1}; Thermal conductivity > 8 W/mK; dn/dT > 8 × 10^{-6}/°K. 6. *Fiber Laser Materials*: Rare earth doped silica glass based fiber lasers with output power >20 Watts and core diameters greater than 10 µm.
Critical Materials	*Laser Materials:* $Ti:Al_2O_3$, Tm-doped garnets (YAG, YSGG, GSGG), Yb-doped garnets (YAG, YSGG, GSGG), $Cr:BeAl_2O_4$, and alexandrite ($Cr:BeAl_2O_4$). Cr:ZnS, Cr:ZnSe. *Sintered Ceramics:* Ultra-high-purity (>99.9999%) polycrystalline precursors of uniform size, along with rare earth dopants at similar purities, are required for sintered material free of defects and voids. Precursor materials necessary for ceramic lasers include $Y_3Al_5O_{12}$, Y_2O_3, Lu_2O_3, and Sc_2O_3. All must be prepared as powders with particle diameters < 100 nm for efficient low-temperature sintering. The rare-earth and transition-metal ion elements useful for ceramic lasers include Nd, Yb, Er, Cr, Dy, Tm, Ho, and Co. *Fiber Laser Materials:* Silica glass fiber with minor additives of P, Al, B, Bi for enhancing solubility of rare earth dopants Yb, Er, Tm, Ho.
Unique Test, Production, Inspection Equipment	*Lasers:* Optical parametric oscillators/amplifiers. *Sintered Ceramics:* Transmission Electron Microscope (TEM), Scanning Electron Microscope (SEM), Transmission/Absorption spectrophotometers.
Unique Software	None identified.
Major Commercial Applications	Scientific and industrial solid-state lasers. Commercial lidar. Industrial fiber lasers. Ceramic lasers may be available as higher efficiency or less expensive replacements for a variety of commercial single-crystal solid-state laser applications, including: • Materials processing (cutting, drilling, welding, marking, heat treating, etc.); • Semiconductor fabrication (wafer cutting, trimming); • The graphic arts (high-end printing and copying); • Medical and surgical, Lasik eye surgery; • Rangefinders and other types of measurement; • Scientific research, spectroscopy, and chemical analysis; (Continued)

Major Commercial Applications (Cont'd)	• Entertainment—laser light shows; and • Scientific applications include DIAL/lidar measurements, optical spectroscopy, combustion analysis, and bio-fluorescence. Large ceramic lasers may sustain much higher power levels than those currently obtainable from small single-crystal lasers, thereby enabling new applications such as laser fusion power generation.
Affordability Issues	Nanoparticle ceramics could significantly lower cost because of reduced cost of electricity and coolant required to manufacture polycrystalline ceramic solids. Yield of ceramic processing techniques compared with current single-crystal processes. Cost of preparing powder precursors with required purity levels. Cost of new equipment (i.e., vacuum sintering) compared to current Czochralski crystal-pulling equipment.
Export Control References	WA Cat 6C; USML XII and XVIII; CCL Cat 6C.

BACKGROUND

High-energy solid-state lasers use transparent crystals, sintered ceramics, or glasses doped with impurity atoms to create high-power laser line emission at a variety of IR wavelengths. Solid-state laser materials have wide absorption spectra, which enables them to be pumped by conventional light sources with wide emission spectra. The impurity atom used as a dopant and the transparent medium into which the impurities are injected both affect the properties of the resulting laser active material. The choice of doping material (such as Nd, Yb, or Cr) determines the lasing energy levels of the material and thus its absorption and emission wavelength. The selection of the transparent lattice material (examples include glasses and crystals of sapphire, garnets, and chrysoberyl) determines the mechanical and thermal properties of the laser material and thus the maximum power levels the material can emit or absorb.

Current solid-state laser technology uses single crystals of high-purity oxide to produce the stimulated emission behavior that defines laser action. Single-crystal laser materials such as YAG containing small amounts of rare earth impurities such as Er, Yb, or Nd, have been optimized to produce laser behavior with high-energy conversion efficiencies. With existing manufacturing technology, however, single-crystal laser rods can only be grown at very high temperatures in expensive iridium crucibles. Growth times for a single crystal vary between four and six weeks, and the size of any single crystal is limited by the maximum dimensions of the crucible fabricated to hold it.

Polycrystalline ceramic materials have recently shown promise as alternative materials for high-energy solid-state laser gain elements. Ceramic materials can be formed using low-temperature sintering processes that take days instead of weeks. Polycrystalline ceramic fabrication does not require expensive crucibles and can be operated rapidly in a production-line fashion. Ceramics are formed at lower temperatures (1/2 to 3/4 the melting temperature of the single-crystal material) and can contain higher concentrations of the rare-earth dopants that generate laser gain than single-crystal materials. Higher doping concentrations lead to higher energy conversion efficiencies and smaller laser elements for the same output power. The reduced temperature of the ceramic sintering process also enables the use of laser oxide materials that are currently impractical by single crystal growth techniques. Yttrium oxide (Y_2O_3) is an excellent solid-state laser material with a high thermal conductivity. Single crystal growth of Y_2O_3 is difficult because it does not melt below 2430 ºC. Polycrystalline Y_2O_3 can be sintered at temperatures close to 1700 ºC, which are much more practical for manufacturing.[2]

When properly formed, the small, randomly oriented grains in polycrystalline ceramics can demonstrate higher thermal conductivity and higher mechanical strength than otherwise identical single crystalline materials. Unlike single crystal laser materials, ceramic materials can be sintered into arbitrary shapes during forming, which enables the formation of near-net-shape complex laser elements without wasted material or additional cutting or grinding steps. Polycrystalline ceramic materials are being used today as optical elements in military systems, where their high strength and high optical transparency make them excellent window materials for visible and IR sensors in

[2] "Yb:doped ceramic makes laser debut," ***Optics.org News,*** April 2003 http://optics.org/articles/news/9/4/23/1.

high-speed aircraft and missile applications. The use of these same materials and new ceramic materials such as rare-earth doped yttrium oxide as laser gain elements could provide benefits leading to smaller, higher power, and more efficient solid-state lasers for a variety of potential military applications.

Rare earth doped single mode silica fibers with core diameters larger than 10 µm, especially Yb doped, have demonstrated up to 3-KW output powers at 1 µm. Similarly, Er doped and Tm doped fibers have demonstrated over 100-W output powers at about 1.5 and 2 µm, respectively. These fibers are sometimes referred to as large mode area fibers. The rare earth ion concentration ranges from a few hundred ppm to many 1000's ppm. Since they are single mode, the output is Gaussian and bright.

Improved technology, especially diode pumping and wavelength conversion, will affect these issues over the next decade as costs decrease and reliability improves in two areas:

- Solid-state high-energy laser constructs, such as arrays of fiber lasers; and
- Lightweight (man-portable) antisensor lasers in 5–25-W category.

Fiber lasers can be used for pumping solid-state single crystal or ceramic laser materials to generate alternative wavelengths, as well as spectrally/spatially combined to generate higher powers.

Ti Sapphire: Broad-band tunable pump source for nonlinear optical/optical parametric oscillator scientific lasers.

Alexandrite: Medical applications, photodynamic therapy, cosmic surgery.

Tm-doped garnets (Tm:YAG and Tm:YSGG): Wind shear lidar and medical applications (i.e., angioplasty).

Chemical and biological detection.

Fiber lasers have uses in biomedical applications, in lidar, and as pump lasers.

MCTL DATA SHEET 11.3-7. PASSIVE OPTICAL LIMITING MATERIALS

This technology is used for filtering unwanted radiation and protecting eyes and sensors from laser radiation.

Critical Technology Parameter(s)	Optical limiting device that: • reduces the incoming fluence to less than 2 μj/cm^2; and • passes at least 5% of the ambient light in its normal state. Any device that uses a passive, optical limiting material to protect the human eye, an electro-optic sensor, or an IR sensor from permanent damage should be export controlled.
Critical Materials	Nonlinear optical materials: • Two-photon absorbers; • Reverse saturable absorbers; and • Semiconductor materials. Nonlinear scattering materials. Rugate filters.
Unique Test, Production, Inspection Equipment	Optical limiting testbed.
Unique Software	Automated deposition software for rugate filter fabrication.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	USML XII.

BACKGROUND

When a threat laser wavelength is known, fixed line filters can be used to protect eyes and sensors from that threat. The technologies for making fixed line filters are known world-wide, with the exception of the rugate filter technology. When the threat laser wavelength is not known or is agile, the technologies incorporating passive optical limiting materials can be used to block threat or hazard pulsed lasers from damaging eyes or sensors. DoD personnel may encounter either laser hazards (misuse of laser rangefinders or target designators, for instance) or actual threat lasers used by an enemy. Protection is afforded against any threat pulsed laser within the operating band of the eye or sensor. It is important that devices incorporating these technologies minimize the reduction in the overall system transmission of ambient light. These technologies can be used to protect eyes, night vision goggles, TVs, CCD cameras, and near-, mid- and far-IR devices. From a practical perspective, this technology is useful only for pulsed, high energy laser threats where peak fluence is of concern. On occasion, a fixed line filter, such as a rugate filter (a narrowband filter that incorporates a gradient refractive index profile normal to the substrate surface), will be incorporated in a passive optical limiting device to add extra protection at a specific wavelength.

The threshold (of laser fluence) at which protection is first afforded and the maximum fluence for which protection is afforded are important properties of these materials. Also important are the overall transmission of the device and its field of view.

There is a significant requirement for this technology by those working (primarily in research) with tunable lasers, or high intensity broadband sources where multiple dopants and co-dopants are used in solid-state host materials.

MCTL DATA SHEET 11.3-8. ACTIVE WAVELENGTH FILTERING MATERIALS

This technology provides active filters that adjust to the wavelength of the threat laser radiation in order to protect eyes and sensors.

Critical Technology Parameter(s)	Active wavelength filtering device that: • Operates at any wavelength between the visible and 15 μm; and • Has an optical density greater than 3 at the blocked wavelength. Any active wavelength filtering devices designed to reduce the effects of laser threats should be export controlled. Although there are many commercial uses for active wavelength filtering, any such device that provides an optical density of greater than 3 should be controlled.
Critical Materials	Nematic liquid crystal filters. Cholesteric liquid crystal filters.
Unique Test, Production, Inspection Equipment	Optical limiting testbed.
Unique Software	Algorithms to control the devices.
Major Commercial Applications	Display applications, welding goggles.
Affordability Issues	None identified.
Export Control References	USML XII.

BACKGROUND

These technologies are used to block threat or hazard continuous-wave laser light of unknown or agile wavelength from passing through to an eye or sensor. DoD personnel may encounter either laser hazards or actual threat lasers used by an enemy. These technologies are designed to sense the wavelength of the threat laser and in some active fashion adjust their characteristics so as to block that wavelength, while letting the ambient light through. It is important that devices incorporating these antijamming technologies minimize the reduction in the overall transmission of ambient light. These technologies can be used to protect eyes, night vision goggles, TVs, CCD cameras, and near-, mid- and far-IR devices.

The optical density [OD = log10(T_λ)], where T_λ is the transmission of the device at the wavelength that is to be blocked, is the most important property of the device. Also important are the number of blocked wavelengths and overall transmission of the filter, goggle, spectacles, or visor that incorporates the blocking.

Although these technologies could be used to make commercial laser protective devices, it would be unusual in the civilian world for workers to be using lasers of unknown wavelengths.

SECTION 11.4—ELECTRO-OPTICAL SENSORS

Highlights

- This section concentrates on the technology for image intensifiers and Focal Plane Arrays (FPA) as generic technologies applicable to many military and civil applications.
- Uncooled FPAs are very significant because of lower cost, size, and weight. Many opportunities for improvements exist.
- Cooled scanned arrays are important in current military systems, but cooled staring arrays are replacing them in future high-performance systems.
- Image Intensifier technology based on vacuum devices has matured. New image intensifier devices, both vacuum and solid state, based on "charge multiplication" have been introduced.

OVERVIEW

The last 40 years of the 20th century brought amazing advances in the ability to create images of scenes at night. The DoD, as well as its counterparts in other countries, largely funded the initial development work. The new technology has revolutionized warfare, as demonstrated in Vietnam, Kosovo, Afghanistan, and especially Iraq. U.S. military forces can now conduct operations at night with efficiency unknown before. General H. Norman Schwarzkopf, commander of the coalition forces during Desert Storm, best characterizes the new capability: "…They couldn't see anything through their sights, and all of a sudden their tank exploded…" (27 February 1991).

There have been orders of magnitude increases in performance since Desert Storm, as well as many new military applications. Night vision technologies undoubtedly had a significant impact on the rapid defeat of Saddam Hussein's forces in Iraq.

Night vision is generally considered to embrace two different technologies, image intensification and thermal imaging. Image intensification, which depends on reflected light from objects in the scene, developed earlier than thermal imaging, from an operational standpoint. Thermal imaging depends on blackbody radiation from objects in the scene.

Image Intensification

Image intensifiers capture ambient light and amplify it thousands of times by electronic means to display the battlefield to a soldier via a phosphor display such as night vision goggles. This ambient light comes from the stars, moon, or sky glow from distant manmade sources, such as cities. A soldier can conduct his combat missions without any active illumination sources using only image intensifiers. The main advantages of image intensifiers as night vision devices are their small size, lightweight, low-power requirements, and low cost. These attributes have enabled image intensifier goggles for head-worn, individual soldier applications and resulted in the procurement of hundreds of thousands of night vision goggles by the U.S. Army. Research and development continues today on image intensifiers in the areas of longer wavelength spectral response, higher sensitivity, larger fields of view, and increased resolution.

Thermal Imaging

Most objects in natural scenes, as well as human beings and manmade objects, emit electromagnetic radiation in the form of heat. Thermal imagers or IR viewers, also known as Forward Looking Infra Red (FLIRs), gather the IR radiation and form an electronic image for the soldier. Since they do not rely on reflected ambient light, thermal imagers are totally light-level independent. They also have significant penetration capabilities through obscurants such as fog, haze, and conventional battlefield smoke. There are two varieties of thermal imaging systems: cooled and uncooled. Cooled thermal imaging requires cryogenic cooling. Uncooled thermal imaging systems require no detector cooling but have sufficient performance to provide the low to medium performance required by individual soldier sights, navigation, and robotics. Current research and development in cooled thermal imaging are pursuing multispectral imaging, improved sensitivity and resolution, and embedded signal processing to aid the soldier in target-acquisition missions. Current uncooled research is directed at smaller size packages and power consumption with lower cost and increased sensitivity, resolution and field of view. Small, palm-sized uncooled thermal imagers are now available.

BACKGROUND

Image intensification, as it exists in the latest third-generation tubes used in aviation goggles, has the highest performance available in the operational inventory. There is a recent development that improves the performance of image intensifiers when there are bright sources in the scene. These sources tend to mask part of the scene in the earlier generations.

Third-generation tubes have essentially the same structure as second-generation tubes, but they use semiconductor rather than multi-alkali photocathodes. Both generations employ microchannel plate electron multipliers. New image intensifier tubes now exist that substitute a “charge multiplication” solid-state device for microchannel plates (see MCTL Data Sheet 11.4-1, Image Intensifier Technology).

First-generation tubes (first introduced into Vietnam in the mid-1960s) had no microchannel plate amplifiers. To achieve enough light gain and not require active illumination at starlight level, it was necessary to couple three together with fiber optic faceplates. These tubes are now obsolete for military applications.

So-called 0 generation refers to S-1 photocathode image converter tubes. These systems required that the scene be illuminated with IR light sources. They became rapidly obsolete after introduction of the first-generation passive starlight scope in the mid-1960s.

Early thermal imaging systems used single-column, optically scanned linear arrays, and some of the operational inventory still has these systems. The next generation uses a focal plane with four or more columns of detectors and is still optically scanned. These systems are often referred to as parallel scanned two-dimensional arrays. Another type of system, favored by UK developers, uses serial scan. The UK invented a way to increase the sensitivity of serial scanners, which usually have fewer detectors than a parallel scanner (sensitivity is proportional to the number of detectors). The scheme (known as SPRITE) allows time delay and integration within a strip of detector material and using a photoconductor operational mode. Upgrades to cooled staring systems are underway, and many planned and operational systems employ staring arrays that require no optical scanning. Third-generation cooled FPAs are now in development. This generation uses FPAs sensitive to two IR bands, Mid Wave Infra Red (MWIR) and Long Wave Infra Red (LWIR) and are staring arrays [see MCTL Data Sheet 11.4-2, Cooled Infrared Focal Plane Array (FPA) Technology].

Uncooled FPAs, which are designed to operate at room temperature, make IR sensors less expensive, lighter, and more reliable. Cost and weight are reduced because the need for expensive, relatively heavy, cryogenic coolers and associated packaging are eliminated. Reliability is improved because almost all moving parts are eliminated and the FPA is no longer subject to the strain of cycling through temperature extremes. Sensitivity of uncooled IR sensors will never be quite as good as that of cooled sensors, however. Therefore, cooled FPAs will always be needed where it is critical to achieve the best detection performance possible.

Thermal Imaging Applications

Significant advances in thermal imaging have occurred since 1969. IR imaging applications are virtually limitless. They allow you to see at night or through haze and smoke. They allow you to measure the temperature profiles of objects at great distances with high accuracy. Military applications now include target acquisition, missile and weapon guidance, navigation, reconnaissance, surveillance, and terrain analysis. Commercial applications exist in many fields: industrial (plant maintenance, quality control, nondestructive testing), environmental and scientific (Earth and solar sciences, pollution control, energy conservation, resource development), medical (mammography, detection of arterial constriction, evaluation of soft tissue injury), and civil (law enforcement, fire fighting, surveillance, border patrol), to name just a few.

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.4. ELECTRO-OPTICAL SENSORS

MCTL DATA SHEET 11.4-1. IMAGE INTENSIFIER TECHNOLOGY

<table>
<tr><td>Critical Technology Parameter(s)</td><td>Image intensifiers having a peak response in the wavelength range exceeding 400 nm but not exceeding 1,800 nm using any of the following:
1. Electron image amplification tubes using any of the following:
a. Microchannel plate with a hole pitch (centre-to-centre spacing) of 12 μm or less; or
b. Electron sensing or photon sensing device having the capacity to achieve charge multiplication.
Any of the following photocathodes:
a. S-20, S-25 or other multialkali photocathodes with a luminous sensitivity exceeding 350 μA/lm;
b. GaAs or GaInAs photocathodes; or
c. Other III-V compound semiconductor photocathodes such as Transferred Electron (TE) photocathodes.
Definition
Charge multiplication is a form of electron image amplification and is defined as the generation of additional charge carriers as a result of an impact ionization gain process. ‘Charge multiplication’ sensors may take the form of an image intensifier tube, solid-state detector or “focal plane array.”
2. Integral gated or nongated power supplies.
3. Electron sensing or photon sensing devices having a peak response in the wavelength range exceeding 400 nm but not exceeding 1,800 nm having the capacity to achieve charge multiplication.
4. Focal plane arrays or solid-state detectors having all of the following:
a. Individual detector elements with a peak response in the wavelength range exceeding 400 nm but not exceeding 1,800 nm; and
b. Capacity to achieve charge multiplication.</td></tr>
<tr><td>Critical Materials</td><td>III-V compound semiconductor photocathodes including GaAs or GaInAs and microchannel plate amplifiers.</td></tr>
<tr><td>Unique Test, Production, Inspection Equipment</td><td>None identified.</td></tr>
<tr><td>Unique Software</td><td>None identified.</td></tr>
<tr><td>Major Commercial Applications</td><td>The commercial applications include industrial surveillance, hunting, search and rescue, and law enforcement; commercial applications are not technology drivers.</td></tr>
<tr><td>Affordability Issues</td><td>Generation-III image intensifiers are quite expensive. They are also too expensive for many civil applications so no cost leverage is available.</td></tr>
<tr><td>Export Control References</td><td>WA ML 15; WA Cat 6A; USML XII; CCL Cat 6A.</td></tr>
</table>

BACKGROUND

Image-intensifier tubes and solid-state image-intensifier-based systems have improved dramatically in the last decade. They are widely used in both military and commercial applications for detecting light photons in low-light-level conditions. These image-intensifier devices are primarily used in items that permit military personnel to see good images in very low light-level conditions.

Generation-I image intensifier tube technology, originally fielded in the 1960s, used multialkali photocathodes and no microchannel plate amplifiers. These were the first passive intensifiers. Previous image tubes required an active source, such as an IR searchlight. The intensifiers had a gain of about 40. To produce an image in starlight it was necessary to cascade three tubes. Generation I is no longer considered as militarily critical.

Generation-II image intensifier tube technology. When microchannel plates (MCP) were introduced in the 1970s it was possible to have sufficient gain in one stage. This made goggles possible and reduced the size and weight of other systems such as weapon sights. Generation-II technology utilizes multialkali (lithium, sodium, potassium, rubidium, cesium, etc.) in the photocathodes

Generation-III technology utilizes III-V compound semiconductor materials in the photocathodes of the image intensifier tubes

The primary difference in the Generation-II and Generation-III tube technologies is the photocathode material. of the image intensifier tubes. Both use microchannel plate image amplifiers. Improvements of particular image intensifier parameters have accelerated these tube improvements. These parameters include responsivity [microamperes per lumen (μA/lm)], resolution [line pairs per millimeter (lp/mm)], and the microchannel-plate channel center-to-center spacing (μm).

A newer technology is now available known as Electron Multiplying Charge-Coupled Devices (EMCCDs). These devices can be substituted for the MCP in image intensifier tubes and this provides a video output instead of a phosphor screen. In this application the EMCCD is responding to electrons from a photocathode.

EMCCDs also exist that respond to visible and infrared photons and can provide a low light level, solid-state sensor.

One of the few significant shortcomings of conventional high-performance CCD cameras is that very low signal levels typically fall beneath the read noise floor of the sensor. An innovative method of amplifying low-light-level signals above the CCD read noise results from incorporating on-chip multiplication gain. The EMCCD achieves, in an all solid-state sensor, the single-photon detection sensitivity typical of intensified or electron-bombarded CCDs at much lower cost and without compromising the quantum efficiency and resolution characteristics of the conventional CCD structure.

MCTL DATA SHEET 11.4-2. COOLED INFRARED FOCAL PLANE ARRAY (FPA) TECHNOLOGY

Critical Technology Parameter(s)	Cooled infrared FPAs in the wavelength range from 1,200 to 30,000 nanometers, as follows: • Linear Cooled FPAs not incorporating time delay and integration (TDI) having 60 or more pixels (1st generation); • Linear Cooled FPAs incorporating time delay and integration (TDI) having 240 × 2 or more pixels (2nd generation); • Cooled staring FPAs having a number of pixels equal to or exceeding 256; or • Dual-Band or Multi-Band Cooled Staring FPAs (3rd generation).
Critical Materials	Photovoltaic HgCdTe on CdZnTe. Photovoltaic HgCdTe on Silicon. CdZnTe wafers. Heteroepitaxial growth of HgCdTe detectors on silicon or germanium substrates of > 2 inches diameter. InSb.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Very limited. Most commercial applications can be addressed by uncooled IR arrays, which cost much less than cooled arrays.
Affordability Issues	Currently, the cryo-cooler accounts for about 25% of the cost of an IR detector assembly; the array and Dewar package is 70% of the cost. Thus, only those applications that require high performance Noise Equivalent Delta Temperature (NEDT) much less than 0.1 K will utilize cooled IR. CdZnTe wafers are only available in sizes up to 2” and from limited sources. Larger wafers would reduce FPA cost.
Export Control References	WA ML 15; WA Cat 6A; USML XII; CCL Cat 6A.

BACKGROUND

The 1st-generation FPAs were used in the DoD Common Module program that was developed and put into production by the U.S. Army Night Vision Laboratory during the 1970s and 1980s. The linear arrays used in the Common Module FPAs were standardized with array sizes of 60, 180, and 240 elements. The Common Module FLIR linear arrays were optically scanned and consisted of a single row of detector elements. They did not use TDI; the display was interlaced that was provided by offsetting the array mechanically on alternate scans.

Systems using these modules are still in use in some U.S. military systems. Co-production also was sponsored in NATO countries and the modules are in use in a number of these countries, as well.

The 2nd-generation FPAs are optically scanned and contain two-dimensional arrays with several columns of elements. They scan in one direction and perform a time delay and integration of the signal in the scanning direction in order to improve the signal-to-noise ratio.

The 2nd-generation upgrade kit allows for broader fields-of-view, as well as increased operating range performance, target detection and identification during day or night, or in adverse weather conditions.

These arrays, known as Standard Array Dewar Assembly (SADA), are incorporated into kits that are designed to:

- Integrate into fielded weapon systems, such as tanks, to replace the lst Generation FLIR Common Modules (B-kit); and
- Provide an IR engine for new weapon systems designs.

The 3rd-generation system under development is capable of viewing targets in the two main atmospheric propagation windows of 3–5 and 8–14 micrometers. The FPA is a large two-dimensional staring array.

MCTL DATA SHEET 11.4-3. UNCOOLED INFRARED FOCAL PLANE ARRAY (FPA) TECHNOLOGY

Critical Technology Parameter(s)	• Pixel count > 10,000. • Pixel linear dimension < 50 μm. • NETD < 100 mK @F /1 optics at 30 Hz frame rates. • Thermal Time Constant ≤ 30 milliseconds.
Critical Materials	• Vanadium oxide (VOx) microbolometers. • Alpha-silicon, (a-Si) microbolometers. • Barium strontium titanate (BST) ferroelectric material. • Amorphous silicon germanium (aSi/Ge).
Unique Test, Production, Inspection Equipment	Equipment for the manufacturing of semiconductor devices or materials.
Unique Software	None identified.
Major Commercial Applications	• Vehicle driver's viewer. • Fire fighting. • Perimeter surveillance. • Home inspection. • Pest control. These applications are not performance drivers compared to most military applications.
Affordability Issues	These are a lower cost option compared to cooled array systems.
Export Control References	WA 6A; WA ML 15; USML XII; CCL Cat 6A.

BACKGROUND

Uncooled FPAs are the principal components of new, low-cost, lightweight thermal cameras. There are numerous civil and military applications.

A number of approaches are being investigated both in the United States and abroad, but the principal, current production devices are based on either vanadium oxide and amorphous silicon (alpha-silicon) microbolometers. BST has been used in some military systems.

The United States has been the early leader in the development of the technology and the production. DoD R&D funding goes back into the 1970s. Now several other countries have production (or preproduction) capability.

Military and civil cameras using the uncooled FPAs have lower performance than those using cryogenically cooled FPAs in the long-wave infrared band and have ghosting/smearing in imaging high dynamic scenes. The smearing results from the time lag from reading out row-by-row or column-by-column and the long time constant for the detector (10–15 ms). The ghosting is the result of reading out two fields (either odd or even) per frame and the time lag associated with the two fields. These problems restrict the applications that uncooled sensors can be used for.

They have advantages in terms of size, weight, and cost, however. Applications such as driver's viewers and small weapon sights are impractical with cryogenically cooled systems in this wavelength region. These applications have used mid-wave IR technology and thermoelectric coolers.

The AN/VAS-5 DVE allows drivers of tactical wheeled and combat vehicles to maintain continuous mission operations, even on a “dirty” battlefield. Because the AN/VAS-5 DVE is a thermal system, it allows drivers to see through battlefield obscurants, promoting a safer driving environment through enhanced situational awareness.

Thermal imagers, such as the uncooled cameras, have advantages over image intensifier systems. One of these advantages is the ability to image through smoke.

There are currently a large number of uncooled IR camera manufacturers worldwide, in countries such as China, Israel, and Turkey; however, there are a limited number of uncooled FPA manufacturers capable of serial production. They are primarily located in France and in the United States, with some capability in a few other countries such as Japan and the UK. Initially, in the early 1990s thick-film BST was the primary material used. Fire-fighting cameras are one of the primary high-volume products. The early ones used BST, which has some advantages over the newer microbolometers—it will withstand high environmental temperatures. But VOx and a-Si microbolometers are becoming the technologies of choice. VOx is more desirable for military applications.

Note that there is very little difference in the technical performance parameters between the cameras sold for civil and military applications. The primary difference is in the military specifications applied to military procurements. The civil cameras tend to be hand-held types similar to a camcorder and are suitable for general surveillance. These configurations do not lend themselves directly to military applications such as weapon sight.

SECTION 11.5—ACOUSTIC SENSORS, MARINE, ACTIVE SONAR

Highlights

- Sonars are the primary undersea warfare sensors of military interest.
- Active sonar systems provide rapid and accurate target location and tracking for developing a quick response fire control solution.
- Major improvements in active sonar systems are necessary to counter the more limiting environmental acoustic conditions found in littoral areas and with the fuel cell/diesel-electric submarines.
- Major operational improvements are to be achieved by improving interference rejection techniques for reverberation and countermeasures.
- Higher ratios of correct decisions to false alarms are required for operation in littoral areas and are being achieved by continued improvements in computer-aided detection, classification and information management.
- Received signal-to-noise levels are being enhanced by data fusion from multiple arrays/platforms and adaptive processing to better match the sonar systems to the acoustic environment.
- Weapons active sonars are being improved to operate at higher speed and resolve, identify and successfully track a high speed, deep diving submarine target.
- It is envisioned that evolutionary improvements in active sonars will continue.

OVERVIEW

This section covers the technologies for the development and production of all active sonars, both military and commercial, which employ acoustic signals to echo range and detect, track, classify and locate underwater objects, including determining the depth of the ocean and highlighting bottom and sub-bottom features. It contains information on data processing, helicopter dipping sonars, sonobuoys, deployed array sonars, underwater weapons and on underwater acoustic mine countermeasures.

BACKGROUND

Sonars are the primary undersea warfare sensors of military interest. They are already vital and will become even more so in the future for effective and safe undersea warfare operations, regardless of whether for open conflict, peace keeping and training or humanitarian efforts. Acoustic sensors are also vital for many civilian endeavors as well. Very low frequency active sonars (streamers) are used to determine potential petroleum bearing features within the earth’s mantle down to 5,000 meters below the ocean floor. It is envisioned that evolutionary improvements in acoustic sensors will continue.

Active sonars are used militarily for antisubmarine and antisurface ship warfare; torpedo and mine homing and targeting; torpedo defense; mine detection and neutralization; swimmer homing and swimmer detection and neutralization; deep-sea salvage; and underwater communication and navigation. Active sonars for antisubmarine warfare (ASW) operate from other submarines, surface ships, aircraft using sonobuoys, helicopters using dipping sonars and from deployed or bottom mounted arrays. Underwater antisurface ship warfare is performed from submarines and by mines. Weapon homing, activation and targeting using active sonar are critical for both mines and torpedoes. Torpedo defense includes soft kill (decoying) and hard kill (antitorpedo torpedoes). Dual uses includes the detection, classification, and tracking of underwater objects, for mapping bottom and sub-bottom features; for submersible operation and navigation, for locating and recovery of objects from the sea floor and for high resolution imaging of cm dimensions for manipulations of underwater objects and equipment. Commercial use is primarily for locating fish, seismic exploration at sea, petroleum and mineral exploitation, and academic studies.

Active sonars are used in conjunction with Passive Sonars in Section 11.6 for all platforms and are impacted by the technology included in Section 11.7, Acoustic Sensors, Marine Platform.

Active sonar performance is highly dependent on the acoustic environment and operating frequency of the system. Propagation loss increases with increasing frequency. Lower frequencies are being selected to gain longer ranges, but have decreasing resolution and require larger arrays. Reverberation from sound reflected back by the ocean boundaries and ocean medium discontinuities is the major interference. Deep ocean propagation paths are direct path (DP), surface duct (SD), bottom bounce (BB), and convergence zone (CZ). For direct path, the projected acoustic beam is curved (refracted) downward by the decreasing sound velocity caused by the decreasing water temperature. The refracted beam leaves a shadow zone at the surface and limits detection ranges to a few thousand meters. Commercial sonars use the direct and surface duct path modes.

A surface duct in the deep ocean is often used in conjunction with the direct path. A surface duct is formed when a thermocline layer exists at around 100 meters depth. The thermocline layer is formed when the water temperature in the layer decreases with depth faster than that of the overlaying and under laying water. The surface and thermocline layer form the boundaries of the duct, which can channel the sonar beam to ranges beyond 10,000 meters. The sonar beam is repeatedly reflected from the channel boundaries where the losses are less than 3 dB.

In shallow (littoral) water of less than 300 meters depth, the available propagation paths are direct and surface duct. The direct path has ranges somewhat less than deep water. The surface duct path is very similar to that of deep water except the beam reflection from the bottom has a much higher loss of up to 10 dB from scattering and absorption than for the reflection from the thermocline layer. For extended ranges, there are typically many bounces. Typical ranges are only a few thousand meters. Transmit power is limited by the increased reverberation. Another drawback is that signals returning from different paths may arrive out of phase and reduce signal strength. In shallow water, the most effective transmission path is determined by the acoustic environment, with the sonar operators selecting the operating mode to best match the environment.

In the BB mode of propagation in the deeper ocean, the acoustic transmitted beam is refracted downward until it bounces off the bottom and then is reflected back toward the surface. The acoustic beam can then detect both submarines and surface ships near the surface in a zone about 3-km wide at around 30- to 40-km range. The reflected signal is then received back at the source via the same path. However, in addition to the propagation loss for the two-way propagation paths, there is bottom loss of 20 to 70 dB for the two-way paths. Bottom loss is both from absorption in the bottom and scattering at the bottom surface. Operational BB with more than 30-dB total bottom loss is very difficult. Another drawback is that signals returning via different paths may arrive out of phase and reduce signal strength. High transmit power and signal-processing gain of over 30 dB are required. BB does not work in the very deep ocean and the transmit and return beams go into the convergence zone mode of operation. The U.S. Navy pioneered the BB mode and is one of the very few navies that use it.

Convergence zone propagation path again uses the same refraction effect to deflect the sonar beam toward the bottom. When the bottom is deeper than about 3,000 meters, the beam is refracted back toward the surface as a function of water pressure before it hits the bottom. This occurs at the depth when the sound velocity is approximately the same as at the surface, i.e., the temperature effect and pressure effect cancel out. This typically occurs around 4,000-meters depth. The transmit beam then converges near the surface in a zone about 6 km wide at about 60- to 70-km range and can detect both submarines and surface ships in the zone. CZ signals do not interact with the bottom, and propagation loss for two-way paths are typically less than half that of BB. The CZ signals are reflected from the surface to facilitate multiple zones. Second and third convergence zones or ranges of over 150 km are possible under good propagation conditions. One drawback is that signals returning via different paths may arrive out of phase and also reduce signal strength. High transmit power and signal-processing gain of over 30 dB are again required. The U.S. Navy pioneered the CZ mode and is one of the very few navies that use it.

A major limit in the use of active sonar is the interference from reverberation, which is created by the backscatter of the transmitted acoustic signal as it passes through discontinuities in the ocean medium and is reflected back from the ocean boundaries. Reverberation has near zero Doppler. Reverberation creates a lot of false alarms and interferes the most when tracking slow speed targets that are difficult to be separated from the reverberation by Doppler processing.

Propagation loss in the ocean is frequency dependent and increases with increasing frequency. The following are the military sonar function versus operating frequency band. (1) Antisurface ship and antisubmarine sonars operate in the 100 Hz to 10 kHz frequency band to obtain ranges out to beyond 30 km. In the shallow water of the littorals, the detection ranges are significantly shorter. (2) Mine detection sonars operate in the 30-kHz to 100-kHz band in order to have increased resolution and, as a consequence, have shorter ranges of up to 2000 meters. (3) Mine *classification*, bottom mapping, and deep sea salvage sonars operate in the 60-kHz to 750-kHz frequency band to obtain the resolution required to discriminate and identify small targets or features from background clutter. Forward-looking and side scan sonars are both used for these purposes. They have ranges out to a few hundred meters, therefore are generally towed near the bottom. (4) The active sonars in underwater weapons operate in the 15-kHz to 25-kHz band and have ranges on the order of 1,000 meters to detect, locate and track the target and provide steering commands. Their lower frequency limit is determined by array size (diameter of torpedo body) and the upper limit is determined by operating range. (5) Imaging sonars operate in the 700-kHz to 2,000-kHz frequency band to provide images with accuracies in millimeters and operating ranges from 1 m to 100 m.

Marine seismic survey systems use a towed 8- to 200-Hz source and a long, towed streamer (towed array) to receive the signals bounced off of features as deep as 6,000 meters in the earth's mantle. By this process, they can locate salt domes and other areas that have potential for containing petroleum products. These systems do not have beamforming and the three-dimensional displays are formed by data processing hundreds of overlapping tracks. Fish finding sonars typically operate in the 20-kHz to 100 kHz-band with ranges from 100 to 2,000 meters, overlapping mine hunting sonars. Depth sounders operate in the 3-kHz to 12-kHz frequency band, overlapping ASW sonars, and typically will determine depth to the bottom of the ocean. Subbottom profilers operate in the 3-kHz to 10-kHz frequency band, again overlapping ASW sonars and can penetrate the bottom up to 50 meters.

Obviously, there is a sizeable amount of overlap between the civilian and military applications. Navy sonars operate monostatically or multistatically from a variety of ships and submarines; from aircraft deploying dipping sonars and sonobuoys; and from moored and bottom mounted locations. Operations are required in all environments. Most active sonar developments have been driven by military use. Civilian sonars are a small but growing part of the active sonar market. They are all limited to direct path and surface duct propagation. Most of them have dual use potential for military application of small ship mine hunting and navigation.

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.5. ACOUSTIC SENSORS, MARINE, ACTIVE SONAR

MCTL DATA SHEET 11.5-1. DATA PROCESSING

Computer-aided data processing reduces reverberation clutter thus increasing correct decisions and reducing false alarms.

Critical Technology Parameter(s)	Advanced statistical signal processing and automated or computer-aided detection, tracking, classification and identification of undersea warfare targets in littoral areas or other cluttered acoustic environments using empirically validated clues (discriminates), decision criteria and decision processes that together provide a probability of over 80% correct decisions with a false alarm rate of less than 20%.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test ships or other platforms at sea recording realistic target and target-like false target data in a variety of locations and seasonal environments.
Unique Software	Using additional at sea-data whenever available, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) signal detection and estimation models of advanced signal processing; (2) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (3) upgrading the algorithms for the discriminating process; (4) identifying and selecting additional clues for upgrading the decision criteria; (5) upgrading the decision criteria; (6) upgrading the algorithms for the decision process; (7) normalizing and thresholding the acoustic signals; and (8) upgrading the algorithms for the normalizing and thresholding process.
Major Commercial Applications	Fish, swimmer and other object detection sonar systems.
Affordability Issues	The cost of sea test to obtain realistic target and target-like false target data, in a variety of seasonal environments and locations is a limiting factor.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Active sonar detection, tracking, classification, and identification of undersea warfare targets in littoral areas or cluttered acoustic environments remains crucial to the success of undersea warfare. Although active sonars are currently successful in their own right, they are still limited by the effects of reverberation and limited ranges from the acoustic operating conditions. Improvements from signal processing and increased transmit power are reaching their limit. Computer-aided process is the leading candidate for improving the probability of detection and correct classification and reducing operator overload.

MCTL DATA SHEET 11.5-2. SIGNAL AND DATA PROCESSING FOR MULTI-SENSORS AND MULTI-PLATFORMS

Data processing reduces reverberation clutter and capability is being expanded by using signals received from multiple arrays and coherently combined.

Critical Technology Parameter(s)	Real-time processing of acoustic data from fixed, deployed or mobile arrays operating in the bi-static or multi-static mode to increase target signal-to-noise ratio by over 6 dB in order to increase detection range by over 10%, increase probability of correct decisions and reduce false alarms.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Bi-static or multi-static platforms at sea to collect data in varying locations and in seasonal conditions.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying, selecting, and upgrading the algorithms for improved signal processing techniques; (2) identifying, selecting and upgrading the algorithms for improved collating of multipath signals from a single sensor; and (3) identifying, selecting and upgrading the algorithms for improved synchronizing, normalizing, adjusting of the dynamic range and performing data fusion of multipath signals coming from a single sensor and from multiple sensors and multiple platforms.
Major Commercial Applications	None identified.
Affordability Issues	The cost of sea test with multiple sensors and platforms to obtain realistic target and target-like false target data in a variety of locations and environments is a limiting factor.
Export Control References	WA ML 5 and 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Active sonar detection, tracking, classification, and identification of undersea warfare targets in littoral areas or cluttered acoustic environments remains crucial to the success of undersea warfare. Although active sonars are currently successful in their own right, they are still limited by the effects of reverberation and limited ranges from the acoustic operating conditions. Improvements from single sensor signal processing and increased transmit power are approaching their limit.

Advance, real-time signal and data processing of active sonar incoming signals from multi-sensors/multi platforms has the potential for substantially increasing signal-to-noise ratio, improving detection range, improving the probability of correct decisions and actions, and reducing the false alarm rate and operator overload. Possible multi platforms are a combination of ships, helicopter dipping sonars, sonobuoys and deployed systems

MCTL DATA SHEET 11.5-3. ADAPTIVE BEAMFORMING

Adaptive beamforming is used to null out strong interfering noise sources, including countermeasures.

Critical Technology Parameter(s)	Improved real-time adaptive beamforming with interference rejection of over 12 dB in order to operate in acoustically cluttered areas, particularly the littorals, and to neutralize countermeasure signals up to 20 dB.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Multiple platforms at sea for collection of target data in the vicinity of interfering contacts, at varying locations and in seasonal conditions.
Unique Software	Using additional at sea-data whenever available, enhance empirically validated set of algorithms that provide an expanded knowledge base for identifying, selecting, and upgrading the algorithms for improved discrimination between interfering signals and signals of interest, refine the decision criteria to reject interference and neutralize countermeasures.
Major Commercial Applications	To minimize interference between fish finding sonars.
Affordable Issues	The cost of sea test to obtain realistic target signals in the vicinity of interfering signals is a limiting factor.
Export Control References	WA ML 4 and 9; WA Cat 6A, 6D and 6E; USML IV, VI and XI; CCL 6A, 6D and 6E.

BACKGROUND

The detection, tracking, classification, and identification of undersea warfare targets remain crucial to the success of undersea warfare. Although active sonars are currently successful in their own right, they are still limited by the effects of interfering contacts and countermeasures. Improved real-time adaptive beamforming that rejects interfering targets or target-like contacts and countermeasures close in to the target submarine has the potential for substantially improving detection range, improving the probability of correct decisions and actions, and reducing the false alarm rate.

MCTL DATA SHEET 11.5-4. REVERBERATION AND COUNTERMEASURE SUPPRESSION

Signal and data processing reduce the reverberation clutter above 3 knots target speed and are being expanded for speeds of less than three knots.

Critical Technology Parameter(s)	Real-time tracking of submarine targets with target speeds of less than three knots that are obscured by reverberation or acoustic countermeasures.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Ships or platforms at sea with high-powered active sonars for collection of additional low speed target data with high reverberation in the background and in varying locations and seasonal conditions.
Unique Software	Using additional at sea-data whenever available, enhance empirically validated set of algorithms that provide an expanded knowledge base for real-time dynamically: (1) identifying and selecting transmit pulse type, coding, length, frequency and frequency agility that minimize the interference received with the variations being based on the reverberation and countermeasure interference being received; (2) normalizing the incoming signals; and (3) adjusting the receiver dynamic range for very weak incoming signals in the presence of very strong reverberation or countermeasure background.
Major Commercial Applications	None identified.
Affordability Issues	The cost of sea test to obtain realistic target and target-like false target data in a variety of reverberation fields and countermeasures is a limiting factor.
Export Control References	WA ML 9 and 11; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The detection, tracking, classification, and identification of undersea warfare targets remain crucial to the success of undersea warfare. Although active sonars are currently successful in their own right, they are still limited by the effects of reverberation and countermeasures. Improvements from other processes are approaching their limit.

Adaptable transmit parameters selected based on the returned signals have the potential of reducing interfering reverberation at target speeds of less than three knots and countermeasures, which will substantially improve the signal-to-noise ratio, detection range and the probability of correct decisions and actions, and reduce the false alarm rate.

MCTL DATA SHEET 11.5-5. CHANNEL ADAPTIVE PROCESSING

A probe pulse is used to determine the medium effects on the signals and adjust system parameters to minimize.

Critical Technology Parameter(s)	Channel adaptive processing using a probe pulse to sample and characterize the medium and to optimize the propagation paths being utilized, has potential for increasing by 100% both signal strength and reliable data rate for underwater acoustic communications.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platforms at sea for collecting additional data in a variety of locations and seasonal conditions in order to formulate the dynamic database.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated set of algorithms that provide an expanded knowledge base for real-time, dynamically identifying and selecting transmit and receive parameters that best match the propagation paths available; with the parameter selections being based on information extracted from the signals returned from the probe pulse.
Major Commercial Applications	None identified.
Affordability Issues	The cost of sea tests to obtain sufficient data in a variety of environmental acoustic conditions in order to formulate the dynamic database, is a limiting factor.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The ability to acoustically communicate between aircraft, surface ships and submarines is vital for multi-platform operations. Long range, underwater acoustic communications are often a subset of the active sonar system. Although current acoustic underwater communication systems are successful in their own right, the range of operation and fidelity of signal are still seriously limited by environmental acoustic conditions.

The capability to dynamically adjust the transmit and receive parameters in real-time to optimally match the available propagation path has the potential for increasing reliable data rate by over 100 percent. This improvement will be most pronounced for littoral areas. Such improvements are especially needed for submarine network centric capability.

MCTL DATA SHEET 11.5-6. ENVIRONMENTALLY ADAPTIVE TRANSMISSIONS

Sonar signals received by multipaths are reduced by multiple arrivals out of phase and reduction can be minimized by selecting more optimum transmit and receive parameters.

Critical Technology Parameter(s)	Dynamically match transmit parameters to measured and historical environmental acoustic conditions in order to minimize multiple arrival of signals that interfere with each other and thereby reduce the signal strength received.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Capability for collecting additional target data in a variety of multipath locations and seasonal conditions in order to formulate the dynamic database.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated set of algorithms that provide an expanded knowledge base for real-time, dynamically selecting and varying transmit parameters of frequency, pulse waveform bandwidth, pulse length and coding, and depression/elevation angle in order to minimize the interference from multiple arrivals. Using the parameters selected, develop models and simulations of typical environments of interest.
Major Commercial Applications	None identified.
Affordability Issues	The cost of sea tests to obtain sufficient data in a variety of environmental acoustic conditions in order to formulate the dynamic database, is a limiting factor. Cost of an expendable, in situ sensors is also an affordability issue.
Export Control References	WA ML 9; WA Cat 6.A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The detection, tracking, classification, and identification of undersea warfare targets remain crucial to the success of undersea warfare. Although active sonar ranges are successful in their own right, they are still limited by the effects of returned multipath signals that arrive by different paths at different times and are out of phase; thereby reducing the signal strength. Improvements from other processes are approaching their limit.

Real time adaptable transmit center frequency, pulse waveform bandwidth, length and coding, and beam depression/elevation angle parameters have the potential of minimizing multipath interferences in open ocean as well as in littoral areas, which will substantially improve the signal-to-ratio and thereby increase the probability of correct decisions and actions, and reduce the false alarm rate.

MCTL DATA SHEET 11.5-7. DATA PROCESSING FOR HELICOPTER DIPPING SONARS

Computer-aided data processing reduces reverberation clutter thus increasing correct decisions and reducing false alarms.

Critical Technology Parameter(s)	Advanced automated or computer-aided detection, tracking, classification and identification of undersea warfare targets in littoral areas or other cluttered acoustic environments employing low (around 1.2 kHz for CZ), mid and high (around 10 kHz) frequencies using empirically validated clues (discriminates), decision criteria and decision processes, providing a probability of over 80% correct decisions and actions with a false alarm rate of less than 20%, all within the size and weight constraints of helicopter dipping sonars.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test platforms at sea recording additional realistic target and target-like false target data in a variety of locations and seasonal environments.
Unique Software	Using additional at sea-data whenever available for all frequency bands, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (2) upgrading the algorithms for the discriminating process; (3) upgrading the decision criteria; (4) upgrading the algorithms for the decision process; (5) identifying and selecting improved clues for normalizing and thresholding the acoustic signals; and (6) implementing the upgraded algorithms for the normalizing and thresholding process. These sets of algorithms are for the functions of detection, classification, identification and tracking of targets and target-like false targets in cluttered acoustic environments.
Major Commercial Applications	Fish, swimmer and other object detection sonar systems.
Affordability Issues	The cost of sea test to obtain realistic target and target-like false target data in a variety of seasonal environments is a limiting factor.
Export Control References	WA ML 9 and 10; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D, and 6E.

BACKGROUND

Detection, tracking, classification, and identification of undersea warfare targets in littoral areas or cluttered acoustic environments remains crucial to the success of undersea warfare. Although helicopter dipping sonars are successful in their own right, they are still limited by the effects of reverberation and limited ranges from the acoustic operating conditions. Improvements from signal processing and increased transmit power are reaching their limit. Computer-aided processing is the leading candidate for increasing signal-to-noise ratio and probability of correct decisions and reducing operator overload.

The obtaining and processing data for surface ship and submarine sonars is applicable for dipping sonars only for special conditions when the operating frequencies are the same. Otherwise the data must be obtained separately with systems operating at frequencies of around 1.1 kHz for CZ operation and around 10 kHz for ASW inner zone operation.

MCTL DATA SHEET 11.5-8. ACTIVE SONOBUOYS

Sonobuoys are dropped from ASW aircraft that deploy a hydrophone and transducer deep in the water, then transmit and receive acoustic signals reflected from potential targets and transmit the acoustic signals by radio to the monitoring aircraft.

Critical Technology Parameter(s)	The real time detection, classification, identification and tracking of submarine targets using mostly in-buoy automated processing and beamforming for an active buoy or from an active adjunct with a passive buoy when operating in littoral areas or other cluttered acoustic environments by using empirically validated clues (discriminates), decision criteria and decision processes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test ships or other platforms at sea recording additional realistic target and target-like false target data in a variety of locations and seasonal environments.
Unique Software	Using additional at sea-data whenever available, expanded data base, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) selecting the transmission signal best matched to the environment; (2) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (3) upgrading the algorithms for the discriminating process; (4) upgrading the decision criteria; (5) implementing the upgraded algorithms for the decision process; (6) normalizing and thresholding the acoustic signals; and (7) implementing the upgraded algorithms for the normalizing and thresholding process. These sets of algorithms are for the functions of detection, classification, identification and tracking targets and target-like false targets in littoral areas and other cluttered acoustic environments.
Major Commercial Applications	None identified.
Affordability Issues	The achieving of relatively low cost for expendable sonobuoys is critical to their acceptance.
Export Control References	WA ML 9 and 10; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

Detection, tracking, classification, and identification of undersea warfare targets in littoral areas or cluttered acoustic environments remains crucial to the success of undersea warfare. Active sonobuoys are a vital part of such operations. Although current active sonobuoys are successful in their own right, they are still limited by the effects of reverberation and limited ranges due to the acoustic operating conditions. Improvements from signal processing and increased transmit power are reaching their limit. Computer-aided process is the leading candidate for improved signal-to-noise ratio, probability of correct decisions and reduced false alarms and operator overload. The SQQ-110 and ALFEA are newer active sonobuoys that serve as the active adjunct for the SQQ-101 passive sonobuoys. See MCTL Data Sheet 11.6-11, Passive Sonars for Sonobuoys.

MCTL DATA SHEET 11.5-9. DEPLOYED SYSTEMS

Active sonar deployed systems are an array of hydrophones laid out in a random pattern in a strategic operating area with an independent sound source for bi-statically detecting stealthy submarine targets in open ocean and littoral areas.

Critical Technology Parameter(s)	Bi-static sonar detection, classification, identification and tracking of quiet submarine targets using air or ship deployed active adjunct projectors and large irregular shaped arrays, in-array automated processing and beamforming for operating in open ocean, littoral areas or other cluttered acoustic environments by using empirically validated clues (discriminates), decision criteria and decision processes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test ships or other platforms at sea recording additional realistic target and target-like false target data in a variety of locations and seasonal environments.
Unique Software	Using additional at sea-data whenever available, expand data base, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) selecting the transmission signal best matched to the environment; (2) identifying and selecting enhanced clues that relate to potential targets and discriminate against target-like false targets; (3) upgrading the algorithms for the discriminating process; (4) upgrading the decision criteria; (5) upgrading the algorithms for the decision process; (6) normalizing and thresholding the acoustic signals; (7) implementing the upgraded algorithms for the normalizing and thresholding process; (8) selecting and implementing the upgraded algorithms for sampling the hydrophones to establish array shape and location; and (9) enhanced adaptable, steered beamforming to enhance targets and minimize interferences and countermeasures. These sets of algorithms are for the functions of detection, classification, identification and tracking targets and target-like false targets in open ocean as well as littoral areas and other cluttered acoustic environments.
Major Commercial Applications	None identified.
Affordability Issues	The achieving of relatively low cost for expendable arrays and acoustic sources is critical to their acceptance.
Export Control References	WA ML 5 and 9; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

Detection, tracking, classification, and identification of submarine targets in littoral areas or cluttered acoustic environments are crucial to the success of ASW. Most successful ASW is performed using a mix of active and passive sonar systems based on the operational scenario. Active sonars are a vital part of such operations. Although active sonars are successful in their own right, they are still limited by the effects of reverberation and limited ranges due to the acoustic operating conditions. Improvements from signal processing and increased transmit power are reaching their limit. One effective approach is to conduct bi-static sonar detection, classification, identification, and tracking of quiet submarines using air or ship deployed active adjunct projectors, long hydrophone arrays deployed on or near the bottom, in-array automated processing and beamforming and using empirically validated clues (discriminates), decision criteria and decision processes. See MCTL Data Sheet 11.6-13, Passive Sonars for Open Ocean Deployed Systems.

MCTL DATA SHEET 11.5-10. ADVANCED ACOUSTIC HOMING TORPEDOES

Acoustic homing torpedoes shift from the passive mode to the active mode for the final 1,000 meters, high-speed run-in to the target.

Critical Technology Parameter(s)	Advanced active sonar for torpedoes having multiple preformed beams with transmit frequency greater than 15 kHz, that acquires the target at extended ranges, at greater depths, and with rapid homing for tracking the target at high speeds and at fast turning rates. This includes advanced automated or computer-aided detection, tracking, classification, and identification of target ships and submarines in littoral areas or other cluttered acoustic environments using empirically validated clues (discriminates), decision criteria and decision processes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test weapons or platforms for collecting additional target data of potential target submarines in a variety of acoustic conditions, including countermeasures, in order to expand and formulate the dynamic database.
Unique Software	Using additional at sea-data whenever available expand data base, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (2) upgrading the algorithms for the discriminating process; (3) upgrading and implementing the algorithms for the decision process; and (4) upgrading the algorithms for the normalizing and thresholding process. These sets of algorithms are for the functions of detection, classification, identification and tracking of targets and target-like false targets in cluttered acoustic environments.
Major Commercial Applications	None identified.
Affordability Issues	The cost of test weapons for collecting target data of potential target submarines in a variety of acoustic conditions, including countermeasures, in order to formulate the dynamic database. The cost of torpedoes and their maintenance remains an issue.
Export Control References	WA ML 4, 9, 10 and 11; WA Cat 6A, 6D and 6E; USML IV, VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

Active sonar is mandatory for the final homing of an acoustic homing torpedo. Acoustic homing torpedoes generally acquire a target from information provided by the launching platform and/or its self-contained passive sonar and then close quietly until they reacquire with active sonar. Since the target is alerted at that time, the torpedo increases speed for the final homing sequence and the passive sonar goes about blind. See MCTL Data Sheet 11.6-14, Passive Sonar for Advanced Acoustic Homing Torpedoes.

MCTL DATA SHEET 11.5-11. ANTI-TORPEDO TORPEDO SYSTEMS

Anti-torpedo torpedoes are employed when an incoming torpedo cannot be acoustically countermeasured.

Critical Technology Parameter(s)	An anti-torpedo shipboard sensor and control system, including: (1) ship mounted high resolution active sonar to rapidly detect, resolve, identify and track salvoes of incoming torpedoes; (2) to launch anti-torpedo torpedoes with heading and bearings to intercept a salvo of incoming torpedoes out to ranges greater than 500 meters; and (3) a high resolution imaging sonar incorporated in the anti-torpedo torpedoes to detect, resolve, and track incoming torpedoes out to ranges greater than 100 meters with a kill accuracy of less than 5 meters.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test facility to collecting additional target data of potential target torpedoes in a variety of acoustic conditions in order to formulate the dynamic database.
Unique Software	Using additional at sea-data whenever available expand data base, enhance and expand empirically validated sets of algorithms for high resolution imaging sonars, both ship mounted and anti-torpedo torpedo mounted that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to incoming torpedoes and discriminate against torpedo-like false targets, including countermeasures; (2) upgrading the algorithms for the discriminating process; and (3) upgrading and implementing the algorithms for the decision process. These sets of algorithms are for the functions of detection, resolution, identification and tracking of a salvo of torpedoes and torpedo-like false targets in cluttered acoustic environments.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 4, 9 and 11; WA Cat 6A, 6D and 6E; USML IV and XI; CCL 6A, 6D and 6E.

BACKGROUND

More and more homing torpedoes are being developed and built that have wake homing and other non-acoustic sensors that cannot be readily countered. Anti-torpedo torpedoes are used to hard kill the threat torpedoes as opposed to the soft kill from acoustic countermeasures, which are often used against acoustic homing torpedoes. Active sonar is a critical ingredient for both the shipboard detection, resolution, identification and tracking of the incoming single or salvo of torpedoes and for the final homing of the anti-torpedo torpedoes. Although active sonars in current torpedoes are successful in their own right, the active sonar in the small diameter of an anti-torpedo torpedo traveling at speeds of over 40 knots, is limited by transmit source level, reverberation, target resolution, angular and Doppler accuracy, and high self noise. Early alertment is expected to come from towed array sonars with directional capability.

MCTL DATA SHEET 11.5-12. MINE HUNTING FROM MCM SHIPS

Critical Technology Parameter(s)	1. Advanced automated or computer-aided detection, tracking, classification and identification of mine and mine-like targets in littoral areas or other cluttered acoustic environments using empirically validated clues (discriminates), decision criteria and processes. 2. An adaptive beamforming process that steers 20 dB nulls toward the bottom and sea surface interfaces to reduce the reverberation interference that almost blanks the mine targets in the water column or near the bottom.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platform available for collecting additional data on mines and mine like targets and reverberation date in a variety of locations in order to formulate and test the dynamic database.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated sets of algorithms that provide an expanded knowledge base to: (1) identify and select additional clues that relate to mines and discriminate against mine-like false targets; (2) upgrade the algorithms for the discriminating process; (3) upgrade and implement the algorithms for the decision process; (4) identify and select additional clues for normalizing and thresholding the acoustic signals; (5) upgrade the algorithms for the normalizing and thresholding process; and (6) upgrade the algorithms for real-time, dynamically tracking and nulling the reverberation from the sea surface and bottom interfaces within the water column. These sets of algorithms are for the functions of detection, classification, identification and tracking of mines and mine-like false targets in cluttered acoustic environments.
Major Commercial Applications	Detecting objects on the sea bottom.
Affordability Issues	The cost for platform availability for collecting data in a variety of locations in order to formulate and test the dynamic database.
Export Control References	WA ML 9 and 11; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The importance of active sonar for mine hunting and neutralization has continued to increase with the worldwide emphasis on littoral warfare and the proliferation of relatively inexpensive sea mines. Sea mines have the potential for sinking or severely damaging high-value units as well as for delaying or removing an option for naval action because of the mine threat to navy vessels and personnel. Active sonar is the most commonly used sensor for detecting, identifying and accurately locating sea mines. Active sonar has the largest area coverage for rapid clearing of a minefield. Although current mine hunting sonars are successful in their own right, they are hampered by reverberation interference and the resulting low signal-to-noise ratio received. Reverberation from the water column interfaces, overloads the sonar receiver circuits and suppresses mine targets in the water column; especially those that are tethered near the bottom.

Detection, tracking, classification, and identification of sea mines in littoral areas or cluttered acoustic environments are crucial to the success of mine warfare. Success is limited by the effects of reverberation and limited ranges from the acoustic operating conditions. Improvements from signal processing and increased transmit power are reaching their limit. Computer-aided process and the ability to null out the water column boundaries' reverberation are the leading candidates for improved signal-to-noise ratio and probability of correct decisions and reducing operator overload.

MCTL DATA SHEET 11.5-13. MINE HUNTING SONARS ON UNDERWATER VEHICLES

Active mine hunting sonars are overwhelmed from reverberation clutter reflected back from the ocean boundaries, obscuring mines.

Critical Technology Parameter(s)	Advanced synthetic aperture, advanced adaptive and advance conventional beamforming sonars on an semi-autonomous underwater vehicles (AUV), 12" or 21" in diameter, launched from an MCM or other warship (organic), having search speeds exceeding 10 knots and operating at better than 1,000-meter range for detection, classification and tracking, and operating in conjunction with an imaging sonar operating better than 100-meter range at slower speeds for further classification and identification; with all three types modes of beamforming sonars incorporating computer-aided detection, identification and tracking of tethered, proud or buried mines and mine-like false targets in littoral areas or other cluttered acoustic environments using empirically validated clues (discriminates), and computer-aided decision criteria and processes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platform available for collecting additional data on mines and mine-like false targets and reverberation date in a variety of locations in order to formulate and test the database.
Unique Software	Using additional at-sea data whenever available, enhance the empirically validated sets of algorithms that provide an expanded knowledge base for: (1) synthetic aperture, advanced adaptive or advanced conventional beamforming; (2) identify and select additional or enhanced clues that relate to mines and discriminate against mine-like false targets; (3) upgrade the algorithms for the discriminating process; (4) upgrade and implement the algorithms for the decision process; (5) identify and select additional clues for normalizing and thresholding the acoustic signals; (6) upgrade the algorithms for the normalizing and thresholding process; and (7) upgrade the algorithms for dynamically tracking and nulling the reverberation from the sea surface and bottom interfaces within the water column. These sets of algorithms are for the SAS, advanced adaptive and conventional search and imaging beamforming sonars, and for functions of detection, identification and tracking of mines and mine-like false targets in cluttered acoustic environments.
Major Commercial Applications	Detecting objects on the sea bottom.
Affordability Issues	Cost for platforms availability for collecting data in a variety of locations in order to formulate and test the dynamic database.
Export Control References	WA ML 9 and 11; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The importance of active sonar for mine hunting and neutralization has continued to increase with the worldwide emphasis on littoral warfare and the proliferation of relatively inexpensive sea mines. Sea mines have the potential for sinking or severely damaging high-value units as well as for delaying or removing an option for naval action because of the mine threat to navy vessels and personnel. Active sonar is the most commonly used sensor for detecting, identifying and accurately locating sea mines and has the largest area coverage for rapid clearing of a minefield. Although current mine hunting sonars are successful in their own right, they are hampered by reverberation clutter and the resulting low signal-to-noise ratio received.

The latest U.S. Navy shipboard mine countermeasure system is the AN/WLD-1 Remote Mine-hunting Sonar (RMS). The RMS is an off-board, semi-autonomous, semi-submersible remotely controlled vehicle to be operated from MCM and other surface combatants. The vehicle contains a mast that reaches above the water line for communication, transmitting data and for precise navigation. It can operate over the horizon. The RMS contains a state-of-the-art ahead looking sonar on the main vehicle to detect, classify and track tethered mines in the water column and a body towed by the vehicle with a state-of-the-art side scan sonar system for detecting, and classifying mines close to or on the bottom. This arrangement allows engagement without high risk to personnel and combatants. The RMS will detects and classify mine threats and mark their position for avoidance and subsequent detonation or removal. The signal and data processing and recording will be performed aboard the host ship and eventually be incorporated into the AN/SQQ-89(V)15 sonar suites.

MCTL DATA SHEET 11.5-14. MINE HUNTING FROM A HELICOPTER

Side scan sonars are used to locate objects near or on the ocean bottom by forming narrow beams in a fan shape to both sides of the transducer and the third dimension is from the movement of the transducer through the water, with forward focused beams to function at speeds greater than 20 knots.

Critical Technology Parameter(s)	Continuous sidescan coverage with greater than 400-m wide swath, combined with forward looking and gap filler sonars, designed to operate at speeds greater than 20 knots, with advanced algorithms and processors for computer-aided detection, identification and location of mines at high operating speed, high-towed body flow noise and operating in medium to shallow water in a cluttered acoustic environment.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated set of algorithms that provide the expanded knowledge base for real-time, dynamically selecting algorithms for processing the received data from overlapping beams, for advanced computer-aided detection, tracking, classification and identification of mines and mine-like targets using empirically validated clues, decision criteria and decision processes.
Major Commercial Applications	High-speed bottom mapping and locating objects on the seabed.
Affordability Issues	Cost for sea tests to obtain sufficient realistic data in many environments to empirically derive information for algorithms and processes are expensive.
Export Control References	WA ML 9, 10 and 11; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

Active sonar is the most commonly used sensor for detecting, identifying and accurately locating sea mines. The importance of active sonar for mine hunting and neutralization has continued to increase with the worldwide emphasis on littoral warfare and the proliferation of relatively inexpensive sea mines. Sea mines have the potential for sinking or severely damaging high-value units as well as for delaying or removing an option for naval action because of the mine threat to navy vessels and personnel. Although current high-speed helicopter towed mine hunting sonars are successful in their own right, there is still need for improved signal to noise ratio resulting in more correct decisions and lower false alarms.

SECTION 11.6—ACOUSTIC SENSORS, MARINE, PASSIVE SONAR

Highlights

- Passive sonars are totally covert and are the sensor of choice in many operational scenarios.
- Major improvements in passive sonar systems are underway to counter the worldwide proliferation of very quiet fuel cell/diesel-electric submarines.
- Target transients, that are difficult to quieten, are being better exploited by employing unique processing and data management.
- Advanced processes are being developed to extend operational target ranges, thereby expanding the search area coverage.
- Computer-aided target detection, classification, identification and tracking are being enhanced and expanded to counter evasive submarine targets.
- Receiving array gain is being increased and self-noise reduced for both hull borne and towed arrays.
- Advanced processes are being developed for reducing the time required for ranging, tracking and developing a fire control solution.

OVERVIEW

This section covers the technology for the development and production of passive sonar systems that are used militarily for the covert location of underwater objects that radiate energy. The radiating energy is created by target vehicle propulsion and maneuvering, flow noise, transmitted acoustic signals, weapons launch, mine and torpedo actuators, and performance of housekeeping functions. The section contains technologies for passive reception, arrays, sonobuoys, deployed array systems, torpedoes and hydrophones.

BACKGROUND

Passive sonars are used primarily for antisubmarine and antisurface ship warfare. Functions performed are the detection, classification, identification, location and tracking of acoustically radiating targets. Passive sonars are incorporated in submarines, surface ships, mines, torpedoes, and bottom mounted and deployed sites. Passive sonar arrays are both mounted on the hulls of and towed from submarines, surface ships and torpedoes. They are also incorporated in helicopters using dipping sonars and in aircraft by using sonobuoy sensors. Passive sonars are frequently used in conjunction with active sonars covered in Section 11.5.

Passive sonar performance is dependent on the acoustic environment. The major interferences are own-ship noise, radiated noise from nearby friendly ships, noise from shipping at long ranges, and other ambient background noise. The ASW passive sonar frequency band has been extended to the lower few hundred hertz as submarines have become quieter. Propagation paths are the same as for active sonar, except the path is only one way (see Section 11.5, ***BACKGROUND***). Detection ranges of thirty to sixty kilometers are possible with towed arrays and hundreds of kilometers are possible with fixed or deployed sites operating against transiting submarine targets. The detection range is shorter for submarine targets operating in the quiet mode or in littoral areas. Underwater weapons passive sonars are designed to operate out to twenty kilometers, while discriminating the target-radiated noise from the weapon self-noise, ambient background noise and possible countermeasures. Unfortunately passive sonars will be less effective in the future as submarines, surface ships and torpedoes become quieter and operate in the noisier littoral locations. This loss will be offset in the future by improved data processing gain and by systems being mounted on several different platforms and networked together (Network Centric Warfare).

Passive sonars have been developed uniquely for naval use. All U.S. Navy passive sonars are U.S. developed and produced. Some advanced technologies are shared with close allies, but relatively few systems are exported.

There are very few civilian uses for passive sonar except for academic research. The major concern is with "active," marine seismic streamers (towed acoustic hydrophones arrays) and ocean bottom cable systems that are daily used for petroleum exploration, but can also be used in the passive mode for submarine detection.

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.6. ACOUSTIC SENSORS, MARINE, PASSIVE SONARS

MCTL DATA SHEET 11.6-1. COMPUTER-AIDED PROCESSING

Computer-aided processing increases signal-to-noise ratio; thereby increasing detection range and correct decisions while minimizing false alarms.

Critical Technology Parameter(s)	Real time, computer-aided detection, classification, and identification of multiple quiet submarine targets traveling at speed of less than 8 knots at ranges out to 60 km in open ocean and 30 km in littoral areas with high probability of correct decisions and low false alarm rates; with real time data to come from one receiver or from multiple receivers already fused together.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platform available for collecting additional target information to be used to improve the database for developing the knowledge base.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (2) upgrading the algorithms for the discrimination process; (3) identifying and selecting additional clues that relate to upgrading the algorithms for the decision process; (4) upgrading the algorithms for the decision process; (5) identifying and selecting additional clues that relate to upgrading the algorithms for data rate reduction; (6) upgrading the algorithms for data rate reduction; (7) identifying and selecting additional clues for upgrading the algorithms for the normalization and thresholding process; and (8) upgrading the algorithms for the normalization and thresholding process.
Major Commercial Applications	None identified.
Affordability Issues	The cost of platform available for collecting target information to be used to improve the database for developing the knowledge base.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Improvement in real time, computer-aided detection, classification and identification of submarine targets based on flow and propulsor noise is a further hedge against submarine quieting as these noise components cannot be as easily reduced.

MCTL DATA SHEET 11.6-2. DATA FUSION

The data received from multiple passive sonars are coherently and synchronously combined to increase signal-to-noise ratio and detection range.

Critical Technology Parameter(s)	Real-time fusion of data received from two or more receiving arrays, including from separate platforms, in order to provide increased overall target signal-to-noise ratio for insertion into the advanced computer-aided processing capability and thereby increase detection, classification and tracking ranges.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated set of algorithms for sorting data by specific coherent target characteristics, accurately upgrading the sorting of like target characteristic, of the decision processes, synchronizing, normalizing and thresholding of data received from multiple sources and combining like data to increase target signal-to-noise ratio and thereby increasing detection, classification and tracking ranges.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The continuing improved quieting of fuel cell/diesel-electric propulsion submarines has been countered with the use of towed arrays and can be further offset by fusing the data from a combination of arrays, including from separate platforms using Network Centric Warfare and other techniques. For data fusion to be effective, the data must be synchronized accurately, coherently and combined based on specific target characteristics. See MCTL Data Sheet 11.6-1, Passive Sonar Computer-Aided Processing.

MCTL DATA SHEET 11.6-3. INTERCEPT RECEIVERS

Intercept receivers are used for detecting impulse type noise or sounds of short duration and non-repetitive nature that are suppressed by the basic passive receiver.

Critical Technology Parameter(s)	Interception of acoustic transients with 360-degrees coverage for the full acoustic spectrum of 10 Hz through 300 kHz and having bearing determination capable of resolving multiple targets with 5-degree separation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platforms to collect additional sea test data to obtain a wider variety of realistic platform and weapon transient signals.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated set of algorithms that provide the expanded knowledge base for: (1) selecting additional clues that discriminate between threat target transients and non threat transients; (2) upgrading the detection, classification and identification algorithms; (3) identifying and selecting additional clues for upgrading the decision criteria algorithms; (4) upgrading the decision criteria algorithms; and (5) time-frequency based algorithm techniques for feature extraction and transient analysis. These sets of algorithms are for the functions of detection, classification and identification of transient signals and determining the bearing of the transient source.
Major Commercial Applications	None identified.
Affordability Issues	The cost of sea test to obtain a wide variety of realistic platform and weapon transient signals and target-like false target signals is a limiting factor.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Passive sonars are designed to detect continuous noise sources, often with a repetitive nature. Impulse type noise or sounds of short duration and non-repetitive nature are suppressed by the basic passive receiver but provide a wealth of information on opposing platform and weapon actions, creating the need for intercept receivers. The challenge is to identify the transient and take appropriate action before the threat submarine can react.

MCTL DATA SHEET 11.6-4. TARGET RANGING

Passive sonar does not inherently have a ranging capability and very special and unique techniques are required to achieve it.

Critical Technology Parameter(s)	Determine target range within five minutes after detection of quiet submarine targets at towed array ranges out to 30 km. Exploit collaboration of multiple arrays from separate platforms with self-localization and networking capabilities to enhance target detection and triangulation to threat targets.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Hull mounted array installation and alignment.
Unique Software	Enhanced empirically validated set of algorithms for: (1) determining target range using irregular array shapes and for determining the array sensor's location and overall array shape; and (2) for exploiting collaboration of multiple arrays from separate platforms with self-localization and networking capabilities to enhance target detection and range by triangulation to threat targets.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Passive sonar does not inherently have a ranging capability. Target range is an important ingredient for an accurate fire control solution. For passive sonar to be effective against targets with standoff weapons, fire control solutions are needed at maximum ranges requiring the use of towed arrays. Ranging from the towed array or towed array combined with the hull-mounted array can be effective for ranging on targets at the maximum detection ranges. The accuracy for this ranging technique is dependent on knowing the location of the array sensors and the overall array configuration.

MCTL DATA SHEET 11.6-5. TARGET BEARINGS

Critical Technology Parameter(s)	Beamforming/spatial processing for target bearing accuracy of less than 1.0 degree using hull mounted and towed arrays at ranges greater than 30 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Array installation and alignment and underwater acoustic test range with operating range of 10 km and accuracy of less than 1.0 degree.
Unique Software	Expanded and enhanced validated set of algorithms for beamforming/spatial processing with data received from both the hull mounted and towed arrays.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Accurate target bearings are an important ingredient for precise fire control solutions. Currently, most fire control solutions are performed using hull-mounted arrays with limited range. Improved target bearings at towed array's longer ranges are being developed to be more effective against targets with standoff weapons. Bearing determination is performed in conjunction with improved adaptive beamforming, null steering and sidelobe reduction capability covered in MCTL Data Sheet 11.6-7, Adaptive Beamforming and Null Steering.

MCTL DATA SHEET 11.6-6. TARGET TRACKING

Multiple target tracking requires very accurate range and bearing information to target and capability to resolve targets.

Critical Technology Parameter(s)	Passive sonar capable of resolving and tracking, within fire control accuracy, multiple submarine targets traveling at various speeds and at ranges out to 30 km.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Enhanced empirically validated set of algorithms that resolve and track multiple targets identified as submarines with accuracy sufficient for a fire control solution.
Major Commercial Applications	None identified.
Affordability	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Accurate target tracking is the critical ingredient for precise fire control solutions. The major objective is the capability to resolve and track multiple, maneuvering targets out to 30-km range in an acoustically cluttered environment. The tracking data is then applied directly to the fire control solution. In those roles, towed hydrophones arrays have increased the detection range of submarines by ten fold and the challenge is to exploit this extended range to advantage in tracking.

MCTL DATA SHEET 11.6-7. ADAPTIVE BEAMFORMING AND NULL STEERING

Adaptive beamforming nulls out interfering noise sources, including countermeasures.

Critical Technology Parameter(s)	Improved real-time, frequency domain and time domain beamforming; adaptive beamforming and null steering processes capable of further reducing interference from acoustic clutter and countermeasures by 10 dB and thereby increasing detection ranges and nullifying countermeasures.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Improve empirically validated set of algorithms for real-time frequency domain and time domain beamforming; adjusting beams and steering nulls to enhance the target signal-to-noise ratio.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The extensive quieting of fuel cell/diesel-electric propulsion submarines in recent years has severely shortened the passive detection range, which is being countered with the use of data fusion from a combination of arrays. Further signal-to-noise improvements can be gained from reducing the interfering noise and clutter received from the environment or from countermeasures using a combination of adaptive beamforming and null steering techniques. Adaptive beamforming, null steering and processes are performed in conjunction with Passive Sonar Target Bearing determination capability covered in MCTL Data Sheet 11.6-5.

MCTL DATA SHEET 11.6-8. ACTIVE NOISE CANCELLATION

Passive sonar self-noise reduced by electronic processes without reducing incoming signals.

Critical Technology Parameter(s)	The real-time reduction of more than 3 dB by active cancellation using electronic processes of (1) platform self-noise that is radiated into the water and received by the passive sonar hydrophones along with the target signals, and (2) of hull borne flow and acceleration self-noise mechanically coupled into the hydrophones, both in order to increase target signal-to-noise ratio and thereby increase detection ranges by 5%.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Using additional at-sea platform data whenever available, enhance empirically validated sets of algorithms that use statistical signal processing to discriminate between platform self-noise and signals of interest and for suppressing the interfering noise without reducing the signals of interest.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Reduction of own-ship noise radiated into the water and received by the hydrophones along with the signals as well as hull-borne noise flow and acceleration noise mechanically coupled into the hydrophones, is one way to increase the signal-to-noise ratio and thereby increase detection range. A reduction of more than 3 dB of own ship self-noise with active cancellation using electronic techniques will help to counter the proliferating quiet fuel cell/diesel-electric submarines. The self-noise reduction using active cancellation is required in addition to the self-noise reduction by passive techniques using baffles, absorbers, conditioners and decouplers.

MCTL DATA SHEET 11.6-9. VOLUMETRIC TOWED ARRAYS

Volumetric towed arrays are several single arrays displaced from each other in a geometric shape and towed together behind the ship or submarine.

Critical Technology Parameter(s)	Capable of increased target detection ranges while maneuvering at tactical speeds by using; multiple but shorter towed arrays; strength members in hose wall; and vibration isolation and low noise dynamic leveling with depression force greater than 100 pounds, both at tow speeds greater than 8 knots.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The extensive quieting of fuel cell/diesel-electric propulsion target submarines is being countered with the use of towed arrays. Further signal-to-noise improvements and extended detection ranges can be gained from towing several shorter arrays (volumetric) instead of one or two long arrays. In addition, the volumetric array arrangement will allow more dynamic tactical maneuvering and higher speeds.

MCTL DATA SHEET 11.6-10. VOLUMETRIC TOWED ARRAY SHAPE AND POSITION DETERMINATION

Volumetric towed array shape and location of discrete points are necessary for towed array data correlation and for range and bearing of targets.

Critical Technology Parameter(s)	Ability to measure or predict within a few meters accuracy, the inter-positioning of discrete points on volumetric towed arrays and to determine their overall arrays shape and position in order to use towed array data for developing fire control solutions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Enhanced empirically validated set of algorithms that provide an expanded knowledge base for determining discrete points along volumetric towed arrays, for determining the inter-position of discrete points, and accurate predictions of their towed array shape and position.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

The extensive quieting of fuel cell/diesel-electric propulsion target submarines is being countered with the use of towed arrays. However, inter-positioning of discrete points on volumetric towed arrays and their overall shape during turns must be known within meters in order to use the data for developing target tracks and fire control solutions.

MCTL DATA SHEET 11.6-11. SONOBUOYS

Passive sonobuoys are dropped from ASW aircraft, then deploy a hydrophone deep in the water, listen for radiated noise from potential targets and transmit the acoustic signals by radio to the monitoring aircraft.

Critical Technology Parameter(s)	The real time computer-aided detection, classification, identification and the determination of the bearing of multiple quiet submarine targets and submarine-like false targets operating out to ranges exceeding 20 km in open ocean, but with emphasis on littoral areas or other acoustically cluttered environments, using a combination of in-buoy and in-aircraft automated data processing and beamforming; all for a passive buoy, but including the capability of receiving and processing signals from active adjunct transmissions as well.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platform available for collecting additional seasonal target information for major operational areas and to be used to improve the database for developing the knowledge base.
Unique Software	Using additional at-sea data whenever available, develop expanded data base, to enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to potential passive and active targets and discriminate against target-like false targets; (2) upgrading the algorithms for the discrimination process; (3) identifying and selecting additional clues for upgrading the decision criteria; (4) upgrading the algorithms for the decision process; (5) identifying and selecting additional clues for normalizing and thresholding the acoustic signals; (6) upgrading the algorithms for the normalizing and thresholding process; (7) identifying and selecting additional clues for data rate reduction; (8) upgrading the algorithms for data rate reduction; (9) identifying and selecting additional clues for adaptive beamforming; (10) upgrading the algorithms for adaptive beamforming; (11) identifying and selecting additional clues for active adjunct operation; and (12) upgrading the algorithms for active adjunct operation.
Major Commercial Applications	None identified.
Affordability Issues	The achieving of relatively low cost for expendable sonobuoys is critical to their acceptance.
Export Control References	WA ML 9 and 10; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

Detection, tracking, classification, and identification of submarine targets in littoral areas or cluttered acoustic environments remains crucial to the success of undersea warfare. Sonobuoys are a vital part of such operations. Sonobuoys are designed to detect, classify, identify and locate or determine the target bearing of quiet submarine targets operating in the open ocean, in littoral areas or other acoustical cluttered environments at ranges out to 20 km.

Success is hindered by limited ranges from the acoustic operating conditions. Improvements from signal processing are reaching their limit. Computer-aided process is a leading candidate for improved signal-to-noise ratio, probability of correct decisions, and reducing false alarms and operator overload.

Current sonobuoy capability has evolved from the original versions developed during WW II, in keeping with the evolving submarine threat. THE AN/CRT-1A was successfully used in WWII. A later version was the broadband SSQ-2. The SSQ-23, the SSQ-28 and then the SSQ-41 narrowband sonobuoys were then introduced and were capable of low frequency analysis and recording (LOFAR) down to 10 hertz. These were followed by the extensively used SSQ-53 series and later the SSQ-77 series with a vertical line array (VLAD), which permits processing out distant shipping noises and high sea state, and reportedly allows operating ranges on the order of 30,000 meters in bottom bounce mode and 60,000 meters using the convergence zone mode of operation, both in the open ocean. Ranges are sharply reduced in littoral areas. A more recent passive/active sonobuoy is the SSQ-101 designed to operate bistatically with the SSQ-110 active source buoy.

MCTL DATA SHEET 11.6-12. DATA PROCESSING FOR HELICOPTER DIPPING

Computer-aided data processing increases signal-to-noise ratio and probability of correct decisions and reducing false alarms.

Critical Technology Parameter(s)	The real time computer-aided detection, classification, identification and the determination of the bearing of multiple quiet submarine targets and target-like false targets while operating out to ranges exceeding 20 km in open ocean, with emphasis on littoral areas or other acoustically cluttered environments, using in-helicopter, automated processing and beamforming; all for the passive mode, but including the capability of receiving and processing signals from active adjunct transmissions as well and thereby providing target location with an error of less than 10% and a false alarm rate of less than 20%; all by using empirically validated clues (discriminates), and advanced decision criteria and processes.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Platform available for collecting additional seasonal target and target-like non-target information for major operational areas.
Unique Software	Using additional at-sea data whenever available, develop expanded data base, to enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (2) upgrading the algorithms for the discrimination process; (3) identifying and selecting additional clues for upgrading the decision criteria; (4) upgrading the algorithms for the decision process; (5) identifying and selecting additional clues for data rate reduction; (6) upgrading the algorithms for data rate reduction; (7) identifying and selecting additional clues for normalizing and thresholding the acoustic signals; (8) upgrading the algorithms for the normalizing and thresholding process; (9) identifying and selecting additional clues for adaptive beamforming; (10) upgrading the algorithms for adaptive beamforming; (11) identifying and selecting additional clues for receiving and processing returned signals from active adjunct operation; and (12) upgrading the algorithms for receiving and processing of return signals from active adjunct operation.
Major Commercial Applications	None identified.
Affordability Issues	The cost of sea test to obtain realistic target and target-like false target data in a variety of seasonable environments is a limiting factor.
Export Control References	WA ML 9 and 10; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

Detection, tracking, classification, and identification of submarine targets in littoral areas or cluttered acoustic environments remain crucial to the success of undersea warfare. Helicopter dipping, passive sonars are a vital part of such operations. Helicopter dipping sonars are designed to detect, classify, identify and locate or determine the target bearing of quiet submarine targets operating in the open ocean, in littoral areas or other acoustical cluttered environments at ranges out to 20 km.

Although helicopter-dipping sonars are successful in their own right, they are limited from the acoustic operating conditions. Improvements from signal processing are reaching their limit. Computer-aided process is a leading candidate for improved signal-to-noise ratio, probability of correct decisions, and reducing false alarms and operator overload.

MCTL DATA SHEET 11.6-13. OPEN OCEAN DEPLOYED SYSTEMS

Passive sonar deployed systems are a large irregular shaped array consisting of hydrophones laid out in a random pattern in a strategic operating area for detecting stealthy submarine targets in open ocean and littoral areas.

Critical Technology Parameter(s)	The real time computer-aided detection, classification, identification and the determination of the bearing of multiple quiet submarine targets and submarine-like false targets operating out to ranges exceeding one convergence zone range (50 to 60 km) using an open ocean deployed array operating in acoustically cluttered environments, using in-array automated processing and beamforming; by using empirically validated clues (discriminates), and advanced decision criteria and processes, with coverage for the frequency spectrum of 10 Hz to 30 kHz. The passive systems also receive and process returned signals from active adjunct transmissions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Using additional at-sea data whenever available, enhance empirically validated sets of algorithms that provide an expanded knowledge base for: (1) identifying and selecting additional clues that relate to potential targets and discriminate against target-like false targets; (2) upgrading the algorithms for the discrimination process; (3) identifying and selecting additional clues for upgrading the decision criteria; (4) upgrading algorithms for the decision process; (5) identifying and selecting additional clues for upgrading the algorithms for data rate reduction; (6) upgrading algorithms for the data rate reduction; (7) identifying and selecting additional clues for the normalizing and thresholding process; (8) upgrading the algorithms for the normalizing and threshold process; (9) identifying and selecting additional clues for upgrading the process for beamforming and compensating for irregular array shape; and (10) upgrading algorithms for compensating for beamforming and irregular array shape.
Major Commercial Applications	None identified.
Affordability Issues	The relatively low cost of the expendable array is critical for effective use.
Export Control References	WA ML 9 and 10; WA Cat 6A, 6D and 6E; USML VIII and XI; CCL 6A, 6D and 6E.

BACKGROUND

A deployed, expendable array that has the potential to cover an ocean basin area provides the best solution for monitoring submarine movements through choke points, straits or barrier situations. Experience has shown that tactical antisubmarine warfare is far more successful if and when adversarial submarine movements are known. With the proliferation of quiet, fuel cell/diesel-electric propulsion submarines throughout the world, the place of engagement will vary from conflict to conflict. Fixed surveillance sites are expensive and limited in use.

MCTL DATA SHEET 11.6-14. ADVANCED ACOUSTIC HOMING TORPEDOES

Critical Technology Parameter(s)	The real-time automated target detection, classification and identification of radiated and flow noise from submarines maneuvering at less than 10 knots at ranges out to 20 km, for achieving target track with an error of less than 20% and for achieving a false alarm rate of less than 10%, and for rejecting countermeasures; all from an autonomous torpedo traveling at over 30 knots.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Nose assembly and body machining.
Unique Software	Using additional at-sea data whenever available, expand the target database, develop empirically validated set of algorithms that provide an expanded knowledge base for: (1) identifying, selecting and weighting the clues that detect, classify, and identify the potential targets and reject false targets; (2) upgrading the automation algorithms; (3) identifying and selecting additional clues for upgrading the decision criteria algorithms; (4) upgrading the decision criteria algorithms; (5) identifying the selecting additional clues for upgrading the target track algorithms; and (6) upgrading the target track algorithms.
Major Commercial Applications	None identified.
Affordability Issues	The achieving of relatively low cost is critical to acceptance.
Export Control References	WA ML 4, 9, 10 and 11; WA Cat 6A, 6D and 6E; USML IV, VllI and XI; CCL 6A, 6D and 6E.

BACKGROUND

The overall objective of the torpedo passive sonar is to reacquire and track the target to within 1,000-m range where the active sonar acquires the target and the torpedo then homes in at high speed and with sufficient accuracy to destroy the target. With the torpedo operating in the passive mode and traveling at modest speeds, counter detection at long ranges is minimized.

MCTL DATA SHEET 11.6-15. FIBER OPTIC HYDROPHONES

Fiber optic hydrophones use coherent laser beams that are modulated by distortion on pressure sensitive coating on the hydrophone optic cable.

Critical Technology Parameter(s)	Fiber optic hydrophones that are on the order of 5 mm (1/4 inch) in diameter; are robust for long life; and with lower array self noise and optical noise; capable of increased signal-to-noise ratio and resulting increase in target detection ranges for deployed arrays, for single and volumetric towed arrays and for arrays mounted on submarines and surface ships.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Seismic streamers (towed arrays).
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Towed acoustic hydrophone arrays, deployed arrays and surface ship and submarine mounted arrays have traditionally used piezoelectric ceramic elements. The ceramic hydrophones are relatively large, affecting the diameter of the array, neutral buoyancy and the susceptibility to flow noise. Fiber optic hydrophones have proven to be capable of longer life, lower self-noise and increased signal to noise ratio.

MCTL DATA SHEET 11.6-16. MINIATURE RELAXOR CRYSTAL HYDROPHONES

Critical Technology Parameter(s)	Miniature relaxor single crystal hydrophones that are on the order of 1 cm in diameter; are robust for long life; capable of increased sensitivity, signal-to-noise ratio and target detection ranges for deployed arrays, and single and volumetric towed arrays.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Seismic streamers (towed arrays).
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL Cat 6A, 6D and 6E.

BACKGROUND

Towed acoustic hydrophone arrays and deployed arrays have traditionally used piezoelectric ceramic elements. The ceramic hydrophones are relative large, affecting the diameter of the array, neutral buoyancy and the susceptibility to flow-noise. Miniature relaxor single crystal element hydrophones have proven to be capable of longer life, having lower self-noise and increased signal to noise ratio.

MCTL DATA SHEET 11.6-17. HYDROPHONES FOR TOWED ARRAYS

Hydrophones using exotic materials or ingenious techniques to increase sensitivity, reduce flow and acceleration noise, or add directionality.

Critical Technology Parameter(s)	Advanced hydrophones for towed acoustic hydrophone arrays incorporating: (1) continuous flexible piezoelectric composite sensing elements, flexible assemblies of discrete piezoelectric sensing elements with dimensions less than 20 mm and separation of elements less than 20 mm, or piezoelectric polymer film sensing elements, with the reduction of hydrophone acceleration generated noise by 10 dB for each type of sensing element; and (2) pressure vector (p-v) sensor sensing elements with the ability to provide directionality of less than 45 degrees.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Seismic streamer (towed acoustic hydrophone arrays) hydrophones.
Affordability Issues	None identified.
Export Control References	WA ML 9 and 11; WA Cat 6A, 6D and E; USML XI; CCL Cat 6A 6D and 6E.

BACKGROUND

Hydrophones are a critical component for any passive sonar array. Piezoelectric ceramic, composites and film remain the major hydrophone sensing elements in use today and have to be improved to counter the quieter fuel cell/diesel-electric propulsion submarines distributed around the world today. The combined reduced flow- and self-noise will significantly increase the signal-to-noise ratio and target detection ranges for individual as well as volumetric towed arrays. Pressure vector (p-v) sensor sensing elements have capability for providing directionality.

MCTL DATA SHEET 11.6-18. TOWED ARRAYS

Towed arrays are long tubes containing numerous spaced hydrophones that are towed underwater behind a vessel to listening for noise generated by submarines.

Critical Technology Parameter(s)	Enhanced towed arrays having increased array sensitivity, reduced self- and acceleration-noise created by the arrays as they are towed through the water, decreased array diameter and to provide information on target bearing in order to increase signal-to-noise ratio and target detection ranges for single and volumetric towed arrays; as well as to improve handling, to prolong array life and to reduce cost.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Seismic streamers (towed arrays).
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL 6A, 6D and 6E.

BACKGROUND

Traditionally towed arrays have used hydrophones with piezoelectric ceramic cylinders or disc as sensing elements. The ceramic hydrophones were spaced in groups to reduce flow noise by spatial averaging and with each two adjacent elements also connected in opposite phase to cancel most acceleration noise. Other piezoelectric hydrophones use continuous flexible composite sensing elements or piezoelectric polymer film stretched over a mandrill, both to obtain increased spatial averaging and sensitivity. Piezoelectric ceramic cylinders and discs, composites and films remain the major hydrophone sensing elements in towed arrays today, have special advantages to warrant further development in order to counter the quieter fuel cell/diesel-electric propulsion submarines being distributed around the world today.

New complex hydrophones using pressure vector (p-v) sensing elements, when assembled into towed arrays, have the ability to provide information on direction of target signals. These hydrophones use one omni-directional piezoelectric ceramic element in conjunction with three axial dipole accelerometers to provide directionality as well as null steering, both of which are a great asset for ASW operations.

Fiber optic hydrophone towed arrays have proven to be capable of longer life, smaller diameter, less cost, have lower self-noise, increased signal to noise ratio and are immune to electromagnetic interference. Fiber optic arrays are touted to be the way of the future and are covered in the Data Sheet 11.6-15 on Fiber Optic Hydrophones.

The combined reduced self-noise of all these types of hydrophones will significantly increase the signal-to-noise ratio and target detection ranges for individual as well as volumetric towed arrays.

SECTION 11.7—ACOUSTIC SENSORS, MARINE PLATFORM

Highlights

- Sonar hydrophones and transducers must be effectively coupled to the seawater without being damaged by the environment.
- Sonar domes and windows are an integral part of the operational platform for the purpose of coupling the hydrophones and transducers to the seawater while protecting the sonar hydrophones and transducers from being damaged.
- Sonar signals absorption and distortion by the sonar domes, windows and there supporting structures, are being reduced to maintain the signal strength and phase coherency in order to obtain maximum signal processing gain and overall sonar effectiveness.
- Platform self-noise coupled into the hydrophones must be reduced in order to increase the sonar signal-to-noise ratio and counter the new, quieter submarine targets.
- Domes and windows are being better isolated from the platform in order to reduce platform self-noise.
- All noise reduction needs to be effective over the depth excursion of U.S. submarines.
- It is envisioned that evolutionary improvements in platform self-noise reduction will continue.

OVERVIEW

This section covers the technology for the development and production of the sonar domes and windows that form the interface between sonar systems and marine platforms. Sonar hydrophones and transducers must be effectively coupled to the seawater without being damaged by the environment and are covered over by sonar domes and windows. These sonar domes and windows are an integral part of the operational platform. This section also covers all equipment, materials and techniques used to reduce platform self- noise that masks incoming signals and reduces the sonars effectiveness. This is most critical for passive sonars covered in MCTL Section 11.6.

BACKGROUND

Sonar domes, windows and self-noise reduction are in direct support of the sonar systems covered in MCTL Sections 11.5 and 11.6 and encompasses all measures taken to reduce the self-noise of ships, submarines, torpedoes and other sonar platforms. Platform acoustic noise control technologies have a major impact on the sonar systems capability by the reduction of self-noise generated by on-ship propulsion, machinery and water flow around the platform. Specifically of interest are sonar domes; windows, baffles; the quieting of machinery, including main propulsion, valves, gears, pumps, fans, balancing and mounting of same, measurement techniques and instrumentation; hull coatings; and active and passive structural noise control. Some of these items are partially covered under ship and submarine signature reduction of radiated noise in MCTL Section 18, Signature Control Technology. Radiated noise and ship self-noise that impacts sonars often come from the same source but the process for reduction of these noises can be quite different and separate.

There are no known commercial uses for the large acoustic domes and windows that are considered militarily critical. All self-noise reduction for marine platforms has been driven by military application. The U.S. Navy developed all of the six acoustic processes covered in this section.

LIST OF MCTL TECHNOLOGY DATASHEETS
11.7. ACOUSTIC SENSORS, MARINE PLATFORM

MCTL DATA SHEET 11.7-1. MARINE PLATFORM ACOUSTIC DOMES AND WINDOWS

Acoustically transparent domes and windows protect the hydrophones and transducers from the elements yet provide water coupling to incoming signals.

Critical Technology Parameter(s)	Withstand wave slap in all sea states, highly damped to reduce transmission of vibrations, can remain submerged for 5 years or longer, do not propagate structural defects, and have low insertion loss at normal incidence for frequencies of 15 kHz or greater.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Underwater acoustic test range for frequencies of 15 kHz or greater.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL Cat 6A, 6D and 6E.

BACKGROUND

The sonar hydrophones and transducers must be effectively coupled to the water without being damaged by marine growth, objects in the water or by wave action and water flow. The hydrophones also need to be isolated from own platform generated noise, turbulent flow noise, and propulsor-generated noise. As such, hydrophones and transducers are acoustically isolated as much as possible from the platform and protected from the ocean by an acoustically transparent dome or window. Unfortunately, structural integrity, acoustic isolation and acoustic transparency are not generally compatible. A group of special materials and techniques have been developed to minimize the problem.

MCTL DATA SHEET 11.7-2. MARINE PLATFORM ACOUSTIC DEVICES AND MATERIALS

Unique devices and materials are used to isolate hydrophones and transducers from on-ship self-noise arriving by all paths.

Critical Technology Parameter(s)	Pressure release for baffles, conditioners and decouplers and attenuation for absorbers, 90% effective for depth excursions of submarines and having an operating life of greater than 5 years; combined flow, propulsor-generated, and self-noise reduction up to 20 dB for sonar frequencies.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Underwater anechoic test facility with pressure capability of 1,000 psi.
Unique Software	None identified.
Major Commercial Applications	None identified.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 6A, 6D and 6E; USML XI; CCL Cat 6A, 6D and 6E.

BACKGROUND

The inside of submarine and surface ship sonar domes contains the structure to physically support the sonar hydrophones and transducers and to support the domes and windows themselves. All of the structures retransmit or reflect ship self-noise into the hydrophones and transducers. Ship self-noise includes flow and propulsor and machinery generated noise. An improved group of special materials, advanced baffles, absorbers, conditioners and decouplers have been developed that have significantly reduced ship self-noise received by the hydrophones and transducers. Increased noise reduction is underway to counter the very quiet fuel cell/diesel-electric submarines.

SECTION 11.8—RADAR TECHNOLOGY

Highlights

- Radar systems, collectively, provide unequalled day-night and adverse weather capabilities for target detection, localization, classification, identification, tracking, and engagement.
- The trend toward smaller unmanned systems and the advance and spread of technologies to measure and model radar reflectivity enables design and operational use of lower radar cross section and thus harder-to-detect threats.
- Rapid advances in enabling technologies have led to significant advances in radar performance at lower cost:
  - Computational resources and signal-processing algorithms make it practical for field radars to employ space-time adaptive processing (STAP) for clutter and interference cancellation.
  - Ultrastable solid-state transmitters with increased reliability, greater average power, and increased transmitter stability are replacing conventional tube technology.
  - Space-based moving target indication (MTI) and synthetic aperture radar (SAR) have become more practical because of lower cost commercial component development for systems such as Iridium or its successors.
- At the same time, advances in computing and RF. components are being driven by pervasive civil applications and are dramatically changing the economics of beam-agile radars.
- Nevertheless, the design and fabrication of radar systems for military applications remains a significant engineering challenge, demanding empirically-validated engineering design models and simulations. Thus, the ability to integrate state-of-the-art systems is not widely available.

OVERVIEW

This section addresses radar technologies at the level of integrated systems. Selected technologies at the subsystem level that are uniquely enabling are also addressed in this section. These include:

- Radar system design for militarily significant applications, as follows:
  - Space-based and airborne imaging radar;
  - OTH Radar;
  - Foliage and ground penetrating radar;
  - Multi-function/track-while-scan radar; and
  - Ground moving target indication (GMTI) radar.
- Radar antenna technology
  - Electronically-steerable arrays (including as a critical subset, conformal arrays); and
  - Low observable antennas.
- Radar power distribution and control
  - Integrated microwave power modules for active arrays; and
  - Optical distribution and control of microwave power.
- Radar receiver and signal processing technology

– Doppler and MTI;

– Space time adaptive processing; and

– Electromagnetic propagation and target characterization, modeling, and simulation.

Technologies for applications of radar to specific mission functions are addressed elsewhere, as follows:

- Radar sensors for target detection and fuzing, including proximity sensors and precision height-of-burst radar altimetry—MCTL Section 2.3, Safing, Arming, Fuzing, and Firing (SAFF);
- Millimeter wave radar, and laser radar for terminal guidance and control—MCTL Section 2.5, Guidance and Control; and
- Ground penetrating radar for countermine detection—MCTL Section 2.9, Mine/Countermine Technology.

Technology for radar mapping and digital scene correlation, also applicable to land attack missile guidance and control, have also emerged as an element of precision positioning and navigation (MCTL Section 16) database reference navigation (DBRN).

Figure 11.8-1 provides a snapshot of key related technologies within the MCTL.

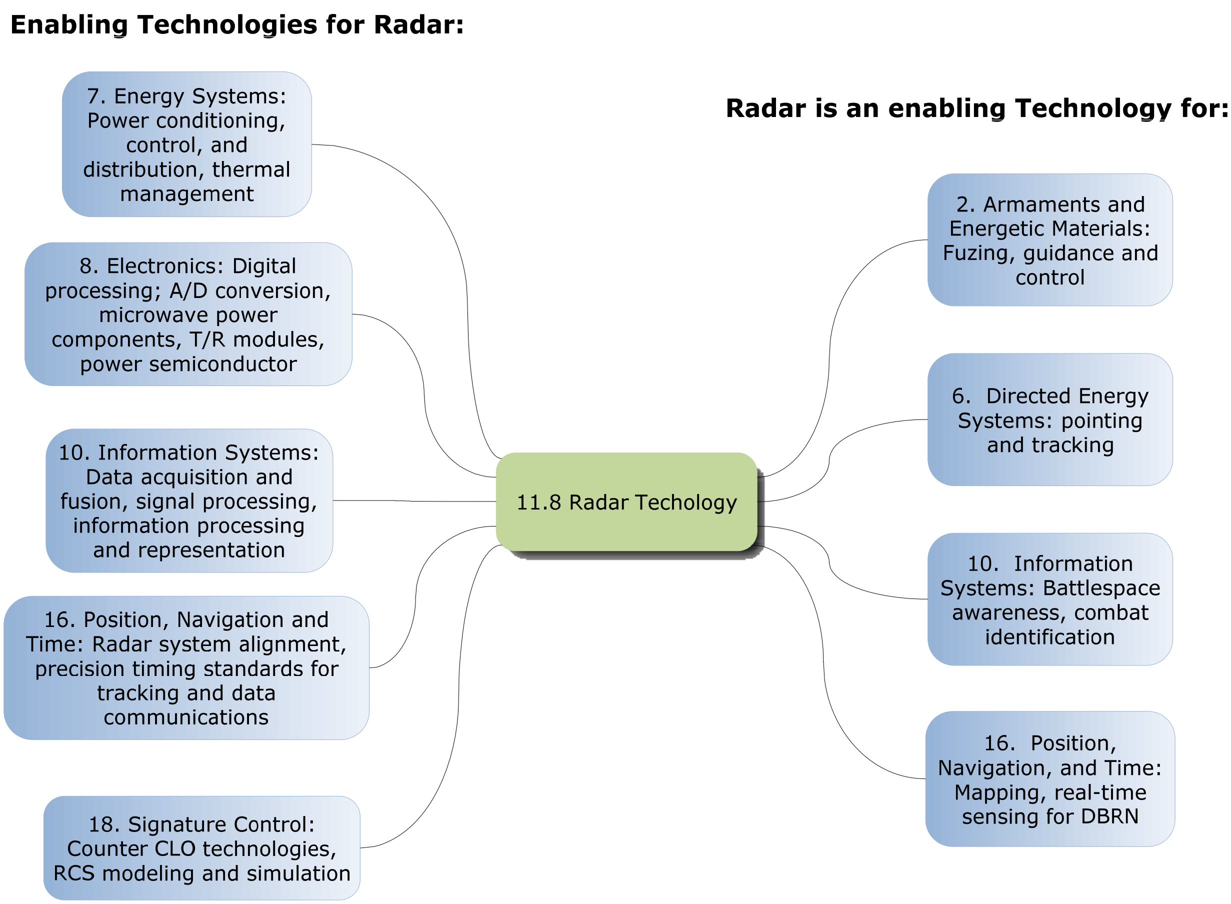


Figure 11.8-1. Related Technologies

BACKGROUND

The term, RADAR, initially from RAdio Detection And Ranging, is defined as:

A device for transmitting electromagnetic signals and receiving echoes from objects of interest (targets) within its volume of coverage. Presence of a target is revealed by detection of its echo, or a transponder reply. Additional information about a target provided by radar includes one or more of the following: distance (range), by elapsed time between transmission of the signal and reception of the return signal; direction, by use of directive antenna patterns; rate of change of range, by measurement of Doppler shift, description or classification of targets, by analysis of echoes and their variation with time.

A note to the IEEE definition (Ref. 1) expands the scope of the term to include so-called passive radar, which exploit signals emanating from the target, and bi-static radar (systems where the transmit and receive functions are geographically separated).

The essential characteristics of radar performance are captured in what is called the "radar range equation," one form of which is as follows:

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

where:

P_r = the power at the receiver;

P_t = the power transmitted;

G = the gain of the antenna;

λ = the wavelength of the signal;

σ = the radar cross section of the target; and

R = the range to the target.

Antenna gain and directivity are a function of the physical size of the antenna, and the wavelength of operation. Specifically gain is ratio of the power radiated by an antenna in a given direction relative to the power that would be radiated by an ideal isotropic radiator (i.e., where the power is uniformly distributed without loss over 4π steradians).

In addition, in applications where the radar is moving relative to the target, for a given relative velocity, the Doppler shift in the signal return is related to the angular position of the target. The Doppler shift can be used to refine the angular resolution (for example, in synthetic aperture or Doppler beam-sharpening radar). Similarly, with higher resolution systems analysis of the range and/or angular distribution of echoes can be used in addition to their time variation to characterize target.

Some crude rules of thumb:

- Beamwidth (in degrees) ≈ 70 λ/d, where d is the physical size of the antenna in the plane in which the beamwidth is measured. Note that 70 is a nominal constant representing a factor that will range from around 50 to better than 100 depending upon the antenna design. Peak Gain ≈ 30000/ $\theta_{el}\ \theta_{az}$ where θ is the half power beamwidth of the transmitted energy.

In practical terms, a one-meter diameter antenna at 10 GHz would have three dB beamwidth of about 2 degrees and a nominal gain of 35 dB. The key characteristics for understanding the military criticality of a given radar system that can be drawn from the radar range equation and the discussion of antennas are that to a first approximation the amount of energy in the signal available to be exploited by the radar receiver:

- Is directly proportional to the transmit power.
- Is directly proportional to the radar cross section of the target.
- Effective radiated power increases as the square of the antenna gain. Antenna gain for a given physical size increases as wavelength decreases. The exact factor is a function of antenna design.

There are also a number of very practical considerations, not reflected in the radar range and antenna equations. These include:

- Power handling capability of a given solid-state device (both power generating and the ability to dissipate losses) is proportional to $1/f^2$, where f is the frequency of operation.
- Atmospheric propagation and multi-path effects, including molecular absorption bands, refraction effects, reflections from precipitation, etc., are all important factors, and vary with frequency.
- Real-world target effects, such as scintillation and glint, which can produce orders of magnitude differences in the apparent size (radar cross section or RCS) as a function of aspect angle, frequency, and (for short-range sensors) range to the point of illumination.
- Noise and clutter, both natural and intentional. Other objects in the field of view of the radar other than the intended targets, reflect or generate electromagnetic signals. A radar will use all of the available parameters (position, motion, detailed target characteristics) to distinguish objects of interest from spurious signals.
- The more complex the environment the greater the signal processing burden. This is an area where the availability of low cost computational power is having a significant impact.

These considerations drive radar design to exploit different portions of the electromagnetic spectrum, from HF to millimeter wave.

LIST OF MCTL TECHNOLOGY DATA SHEETS
11.8. RADAR TECHNOLOGY

MCTL DATA SHEET 11.8-1. FOLIAGE PENETRATING RADAR

Technology for detecting targets concealed by foliage/other clutter.

Critical Technology Parameter(s)	Airborne radar having any of the following design features to detect and localize features and targets through foliage: • Design and use of airborne VHF/UHF SAR techniques to enhance spatial resolution of airborne FOPEN sensors; • Development and use of reliable signal and information processing techniques for target detection and classification, including use of frequency diversity (instantaneous spread spectrum, stepped, or harmonic), polarization agility/discrimination; • Development of target models and simulations that accurately characterize the scattering and reflective properties of foliage, targets of interest as well as the properties of targets of interest viewed through foliage; and • ECCM and LPI techniques, particularly for tactical stand-off detection systems.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	• Target models and simulations that accurately characterize the scattering and reflective properties of foliage, targets of interest as well as the properties of targets of interest viewed through foliage. • SAR/SLAR signal and data processing techniques including: – Space-time adaptive processing. – Techniques for sub-clutter target classification and moving target indication.
Major Commercial Applications	FOPEN radars are being actively pursued for remote sensing of earth resources.
Affordability Issues	While cost is a consideration, growing availability of low-cost radio-frequency components and computational power from the civil sector has reduced, and will continue to reduce the cost of FOPEN technology.
Export Control References	WA Cat 6 and CCL Cat 6 categorically control all SLAR, SAR and ISAR radars, which is necessary and sufficient to control critical aspects of airborne FOPEN radar. Techniques for foliage penetration for off-road ground robotics are not explicitly covered and a proposal should be considered to add coverage as a sub-item under 6.A.8.l.

BACKGROUND

Radar is the primary sensor for all-weather detection of air, ground, and subsurface targets. It includes wide area surveillance radars, tactical reconnaissance radars, and airborne and ground fire control radars.

Foliage penetration (FOPEN) radar is currently being pursued by the military as a means to detect targets of interest hidden by forest canopy and camouflage. The current state of the art, prototypes and operational systems typically employ at least one frequency band in the UHF band or below. Work in FOPEN involves the phenomenology of ultrawideband or multifrequency synthetic aperture radar (UWB/SAR), polarization agility, and harmonic radar techniques to enable detection and classification of stationary targets that are concealed by earth, foliage or camouflage. Foliage penetration and ground penetration systems are a major goal identified in the ASTMP. (Ground penetrating radars are a primary candidate for mine detection and are currently addressed in Armaments and Energetic Materials, Section 2.9 Mine/Countermine Technology.)

The critical operational requirement for this class of radars is to achieve an acceptable ratio between probability of detection (Pd) and probability of false alarm (Pfa). This ratio is dependent upon a number of different variables, including effective radiated power (ERP), system noise characteristics, relative magnitude and spatial/spectral characteristics of backscatter and reflection from targets, natural surroundings (clutter) and artifacts (potential false targets), and the specific detection scheme and signal processing gain.

MCTL DATA SHEET 11.8-2. GROUND MOVING TARGET INDICATING RADAR

Ground moving target indicating (GMTI) radar focuses on technologies for air- and space-borne radars designed to discriminate and categorize slow-moving ground and low-flying targets. It encompasses all techniques, including simpler single aperture techniques suitable for use on small UAV platforms.

Critical Technology Parameter(s)	Development and production of radar hardware specially designed to support extraction of relative motion of targets in clutter from a moving platform, and development and operational use of experimentally validated algorithms and associated data bases for extraction and processing GMTI features.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Modeling and simulation software, with any of the following features: • Experimentally-validated statistical models of ground targets in complex clutter environments; • First principles physical models of complex geometrical targets, clutter, and propagation effects; and • Modeling and simulation of radar performance characterizing and incorporating compensation for platform motion.
Major Commercial Applications	At present, GMTI is predominately military in nature. However, as the technology matures and more sensors are deployed, there are obvious applications for monitoring moving ground targets both as a sensor for homeland security, and as an instrument for measuring traffic flow to evaluate transportation systems, and potentially for collision avoidance.
Affordability Issues	Will become an issue as such systems migrate to lower-cost medium altitude and endurance UAVs.
Export Control References	WA Cat 6.A.8.g. Specially designed for airborne (balloon or airframe mounted) operation and having Doppler “signal processing” for the detection of moving targets. CCL Cat 6A008.g.

BACKGROUND

Ground moving target indicating radars apply a variety of techniques to unambiguously distinguish between static background and moving targets. The term is generally interpreted as applicable to detection of both ground vehicles and low-flying slow aircraft (such as helicopters flying nap-of-the-earth). Techniques range from simple change detection, to sophisticated Doppler processing techniques [including as a special class, space-time adaptive processing (STAP)] to separate moving targets embedded in returns from a single radar resolution cell. In addition to advanced signal processing techniques, also discussed in MCTL Data Sheet 11.8-9, Radar Signal Processing Technology, the basic architecture and antenna configuration of the radar, and its integration with the platform come into play. More advanced concepts will involve the use of displaced phase center antennas and space time adaptive processing to enhance endo-clutter visibility of moving targets.

The performance of air or space-borne GMTI is a function of a number of complex and inter-related factors relating to: system architecture; platform dynamics; detection envelop, range and angular resolution; spectral characteristics and propagation; and target and background scattering and reflectivity characteristics. Some form of Doppler processing is frequently used to discriminate moving targets. As a practical matter, GMTI requires the use of sophisticated algorithms to analyze and correlate data across multiple looks at a given point on the ground to determine the presence of a moving target.

MCTL DATA SHEET 11.8-3. LASER/LIGHT DETECTION AND RANGEFINDING (LADAR/LIDAR) AND REMOTE SENSING

Technologies for development, production, and use of laser radar, LADAR, LIDAR, and imaging laser radar systems.

Critical Technology Parameter(s)	LADAR/LIDAR systems comprising any of the following features: • Space-qualified LADAR/LIDAR systems; • Employing coherent processing techniques, including homodyne or heterodyne receiving techniques; • Employing optical synthetic aperture techniques; • Employing wavelength or polarization agility; • Capable of better than 10 cm resolution from a standoff range of > 1 km or greater; or • Capable of imaging, feature extraction, and pattern recognition for automated or computer-assisted characterization or identification of environmental features and artifacts from a moving platform. These critical parameters are not intended to cover LADAR/LIDAR designed for cooperative navigation and control based on fixed reflectors for providing way-point coordinates.
Critical Materials	Solid-state laser materials, optical coatings and materials as described in Section 11.3, Optical Materials.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Experimentally-validated modeling and simulation of propagation and scattering characteristics, specifically those that will allow design of artificially-intelligent systems for distinguishing between different categories of objects (e.g., hedges vs. stone walls). Real-time predictive modeling and simulation of propagation, particularly experimentally-validated models using first principles modeling valid across a wide range of atmospheric conditions.
Major Commercial Applications	• Airborne lidar mapping of high resolution digital elevation data. Examples include profiling of construction and construction sites and measurements and assessment of construction damage after catastrophic events. • Laser profiling for industrial machining process control. • Laser vibrometry for non-contact inspection, vibration analysis, and non-destructive evaluation (NDE). • LADAR/LIDAR for autonomous ground vehicle navigation and control. • Atmospheric sounding, including Raman LIDAR spectroscopy, and use of coherent Doppler techniques for determining velocity (wind speed and particulate transport characteristics). • Remote imaging sensing geophysical and for earth resource monitoring.

Affordability Issues	Current LADAR technologies used for commercial airborne lidar mapping and ground-based high-resolution 3D lidar scanning applications will face affordability challenges as they are migrated to more demanding and more agile platforms and are more widely proliferated. Affordability will be a consideration for expendable ordnance [e.g., the Low-Cost Autonomous Attack System (LOCAAS)] and to a lesser extent for certain unmanned ground vehicle (UGV) applications.
Export Control References	LADAR/LIDAR systems are controlled under WA Cat 6.A.8.j. and the CCL Cat 6A008.j. if they are either space qualified, or have an angular resolution of better than 20 microradians.

BACKGROUND

LADAR/LIDAR exploits the scattering characteristics and shorter wavelength and high directivity of laser energy to image objects at much finer resolution than is readily attainable with longer wave millimeter and microwave systems. This data sheet addresses technologies for real-time (or near real-time) imaging of terrain, environment, and objects in two or more dimensions. Technology for specific applications is found elsewhere in the MCTL, specifically: Section 2, Data Sheets 2.5-1 Active Laser Seeker, and 2.9-5 Countermine, Stand-Off Land Mine Detection.

Technologies for lasers, optics and critical materials for lasers and optics are addressed in Sections 11.1 Lasers, and 11.3 Optical Materials.

MCTL DATA SHEET 11.8-4. OVER-THE-HORIZON (OTH) RADAR

Development, production, and operational use of ground- and sea-based radar capable of detecting and localizing targets over-the-horizon.

Critical Technology Parameter(s)	Radar systems specially designed for over-the-horizon (OTH) detection and tracking of air or surface targets through use of either of the following: • Operating in the high frequency (HF) (3–30 MHz) and employing ionospheric reflection for OTH propagation; and • Ducting that is trapping and guiding of radar signals due to gradation in index of refraction as a function of height caused by local atmospheric conditions. Or having one or more of the following features: • Signal processing techniques for detection and localization of targets in clutter; • Signal processing techniques for dealing with multipath phenomena; • Doppler processing; and • Designed for bistatic/multistatic operation.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Experimentally-validated signal process algorithms for clutter rejection and target detection and localization, including Doppler processing techniques for MTI and beam sharpening. Predictive models for predicting propagation characteristics.
Major Commercial Applications	The only references found were to use of U.S. Navy Relocatable OTH Radar (ROTHR) for monitoring drug trafficking activities, and use of the French NOSTRADAMUS system for atmospheric sounding (Refs. 1 and 2).
Affordability Issues	Not an issue. HF OTH radars are highly-specialized, low quantity production systems.
Export Control References	OTH radars as a category are not explicitly controlled for national security under either the US or WA dual-use lists. Specific designs may be captured by virtue of specific features (spectral characteristics or data processing features) defined in WA Cat 6.A.8 or CCL Cat 6A008. All OTH radars extant would be categorically covered by USML Cat 11. No comparable language is provided in the WA ML.

BACKGROUND

OTH radar comprises three different conceptual approaches:

- Use of HF ionospheric bounce to project radar energy over the horizon.
- Ducting, specifically gradation in refractive index due to localized atmospheric effects.
- Surface wave diffraction, also referred to as "creeping waves."

HF ionospheric bounce systems have been designed and operated for military use. Ducting is a phenomenon that has been observed with conventional radar and may be exploited opportunistically to extend the effective detection range of shipborne radars.

MCTL DATA SHEET 11.8-5. PHASED ARRAY RADAR (INCLUDING MULTI-FUNCTION/TRACK-WHILE-SCAN)

Phased array radar encompasses a wide variety of concepts, the common characteristic of which is that phasing of signals across a multi-element array is used to shape and direct the radar energy. This includes the ability to control signal phase and amplitude in real time (specifically on a pulse-to-pulse basis) to perform multiple functions simultaneously.

Critical Technology Parameter(s)	Radar systems meeting all of the following parameters or technical criteria: • Employing electronically scanned arrays having the characteristics defined in MCTL Data Sheet 11.8-8, Electronically-Steerable Arrays (ESA). • Providing simultaneous track-while-scan capabilities. Or having any of the following specific features: • Graceful degradation of operation due to damage from ballistic impact or other damage mechanism characteristic of military threats, including exposure to electromagnetic pulse radiation (including lasers) or ionizing radiation effects. • Signature management features, active or passive, including automatic emission controls, adaptive null steering, or use of low probability of intercept wave forms. • Specially-designed for airborne/space-based operation. • Incorporating electronically-tunable “radar frequency agility” exceeding plus or minus 6.25%, or incorporating modulation techniques to distribute energy originating from a signal with a relatively narrow frequency band, over a much wider band of frequencies, by using random or pseudo-random coding (“radar spread spectrum”).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Anechoic chambers specially-designed for near-field measurement in an aerospace environment.
Unique Software	Experimentally validated modeling and simulation of electromagnetic characteristics (e.g., mutual impedance) and resulting antenna pattern characteristics for complex (non-planar) conformal arrays. Test applications software for any of the following: • Post-assembly digital alignment providing accurate compensation for mechanical assembly tolerances; and • Boresight compensation for radome tolerances. Radar applications software, as follows: • Digital beam shaping and pointing control and digital signal processing applications, including those incorporating techniques for adaptive null steering, spread spectrum operations, compensation and adjustment for battle damage; and • Incorporating techniques for dynamic control of phased array retroreflectivity for low observables.
Major Commercial Applications	Because of cost considerations, phased array radars have found limited use in civil applications, specifically in air traffic control and, in one limited application, weather radar. Antenna technology, in the form of rudimentary linear arrays with a limited number of elements, have found application in cellular communications, where beam agility facilitates alignment and reduces the cost of installation.

Affordability Issues	Historically, the cost of phased array radars has been a significant barrier to their adoption and use. This picture is rapidly changing because of the combined effect of wider use and thus availability of microwave and mixed signal components and assemblies (including microwave and millimeter wave power modules) for consumer product applications, and the inherent ability of active array technologies for post assembly digital alignment and compensation.
Export Control References	Phased array radar systems are explicitly controlled under CCL Category 6A008e, as Radar incorporating "electronically-steerable phased array antennae," and under the corresponding WA Cat 6.A.8.e. Technology is controlled in Part E. of each control.

BACKGROUND

Electronically scanned antennas are a critical enabling technology for modern phased array radars. Primary mission applications have included air defense surveillance and track-while-scan radars, tactical ballistic missile defense, and counter-battery location systems. Planar ESA represent the mature state of the art, and so-called passive arrays (that is configurations where the signal is fed at full power to an antenna consisting of passive phase shifters and antenna elements) have been in use since around 1970.

Current emphasis is on the development of active arrays where signals are distributed at low-power and the final stage of amplification is integral to the antenna element itself. Non-planar conformal arrays represent the leading edge of the art, [and the design of broadband arrays with low-side lobe performance (an ECCM feature) is particularly challenging because of the difficulty of characterizing what are known as "mutual impedance effects" in a complex geometry].

MCTL DATA SHEET 11.8-6. SPACE-BASED AND AIRBORNE IMAGING RADAR TECHNOLOGY

Technologies for development, production and use of high resolution synthetic aperture (SAR), inverse synthetic aperture (ISAR) or other side-looking radar (SLR) techniques.

Critical Technology Parameter(s)	Development, production, and use of space or airborne imaging radars providing any of the following features: • Spatial resolution better than 3 meters; • Geographic resolution better than 5 meters; • Real-time imaging; • Specially-designed or modified to enhance capabilities for multiple-pass or split aperture interferometric techniques; • Space-time adaptive processing; • Doppler processing techniques; and • Moving target/target height discrimination.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially-designed vacuum chambers for space-qualification of radar systems.
Unique Software	Experimentally validated modeling and simulation of radar performance and target features. Signal and data processing applications embedding algorithms to enhance the systems' abilities to extract meaningful features, and classify, localize, and identify specific geographical features (including as an important subset, man-made objects and structures).
Major Commercial Applications	Earth resource mapping, including both natural resources and mapping of human activity such as patterns of land use and development.
Affordability Issues	Has not been an issue because such radars have typically been high-value added ISR assets, deployed on expensive space or manned aircraft platforms. As the technology migrates to use on lower-cost and potentially expendable UAV platforms, cost will become more of a factor.
Export Control References	WA Cat 6.A.8.d and EAR Cat 6A008.d categorically control all radars, “Capable of operating in synthetic aperture (SAR), inverse synthetic aperture (ISAR) radar mode, or sidelooking airborne (SLAR) radar mode.” All specially designed software for their “development” or “production,” or “use” is explicitly controlled by the present language, as is technology, by reference to the General Technology Note in 6.E.1 and 6.E.2. Space-based radars: USML XV(e) which also covers spacecraft test facilities.

BACKGROUND

Using the motion of the radar and target, with appropriate delays and correlation to create a virtual array allows space-based and airborne SAR, SLAR, and ISAR to construct very high resolution images. Initial concepts used photo-optical post processing techniques. Modern high-performance microprocessors, however, now allow images to be extracted and stored onboard in real time.

Past and current space-based systems have generally operated in C-band, but frequencies between L- and X-band have also been used. The synthetic aperture technique provides inherently high resolution without the transmission loss penalties imposed by higher frequencies. UHF SAR is an important enabling technology for foliage penetrating radar (see Data Sheet 11.8-1, Foliage Penetrating Radar Technology for specific coverage).

MCTL DATA SHEET 11.8-7. ELECTRONICALLY-STEERABLE ARRAYS

Technology for electronically-controlled phased arrays capable of rapid (pulse-to-pulse) changes in antenna beam characteristics.

Critical Technology Parameter(s)	Electronically steerable arrays designed to provide any of the following features: • Spatial beam agility on a pulse-to-pulse basis; • Wide-band frequency-modulated continuous wave (FMCW) operation; • Non-planar array configurations (conformal arrays); • Non-uniform distribution of antenna elements in the array; and • Adaptive beamforming, including sidelobe cancellation or adaptive null-steering.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Near-field measurement ranges.
Unique Software	Experimentally validated modeling and simulation of electromagnetic characteristics (e.g., mutual impedance) and resulting antenna pattern characteristics for complex (non-planar) conformal arrays. Test applications software for any of the following: • Post-assembly digital alignment providing accurate compensation for mechanical assembly tolerances; and • Boresight compensation for radome tolerances. Radar applications software, as follows: • Digital beam shaping and pointing control and digital signal processing applications, including those incorporating techniques for adaptive null steering, spread spectrum operations, compensation and adjustment for battle damage; and • Incorporating techniques for dynamic control of phased array retroreflectivity for low observables.
Major Commercial Applications	Because of cost considerations, phased array radars have found limited use in civil applications, specifically in air traffic control and, in one limited application, weather radar. Antenna technology, in the form of rudimentary linear arrays with a limited number of elements, have found application in cellular communications, where beam agility facilitates alignment and reduces the cost of installation.
Affordability Issues	Historically, cost has been a significant barrier to wide adoption of ESA technology. This picture is rapidly changing because of the combined effect of wider use and thus, availability of microwave and mixed signal components and assemblies (including microwave and millimeter-wave power modules) for consumer product applications, and the inherent ability of active array technologies for post assembly digital alignment and compensation.
Export Control References	Electronically-steerable arrays for radar systems are explicitly controlled as assemblies or specially-designed components, under CCL Cat 6A008e. Radar incorporating "electronically-steerable phased array antennae," and under the corresponding WA Cat 6.A.8.c. Technology is controlled in Part E. of each control.

BACKGROUND

Electronically scanned antennas are a critical enabling technology for modern phased array radars. Primary mission applications have included air defense surveillance and track-while-scan radars, tactical ballistic missile defense, and counter-battery location systems. Planar ESA represent the mature state of the art, and so-called passive arrays (that is configurations where the signal is fed at full power to an antenna consisting of passive phase shifters and antenna elements) have been in use since around 1970.

Current emphasis is on the development of active arrays, where signals are distributed at low-power and the final stage of amplification is integral to the antenna element itself. Non-planar conformal arrays represent the leading edge of the art, [and the design of broadband arrays with low sidelobe performance (an ECCM feature) is particularly challenging because of the difficulty of characterizing what are known as “mutual impedance effects“ in a complex geometry.]

MCTL DATA SHEET 11.8-8. OPTICAL DISTRIBUTION AND CONTROL OF MICROWAVE POWER

Technology for optical distribution or control of microwave energy. This includes advanced modulation techniques for using optical signals as carriers of microwave signals for distribution, time delay or phase control, as well as optically-controlled devices for switching and phase control.

Critical Technology Parameter(s)	Components for distribution or control (including switching, time delay, or phase control, having any of the following characteristics: • Use of optical energy as a carrier for radio-frequency signals exceeding 300 MHz; • Optical delay lines incorporating any of the following features: (1) optical amplification; (2) variable time-delay; (3) specially designed with compensation to control dispersion to maintain spectral fidelity for broad-band microwave signals; and • Optical switching or phase control of microwave energy.
Critical Materials	• Low-loss/low dispersion optical fibers. • Non-linear optical materials, as defined in Section 11.3.
Unique Test, Production, Inspection Equipment	Specially-designed instrumentation for comparing the spectral characteristics of optically-transmitted microwave signals to the original microwave signals.
Unique Software	Experimentally-validated predictive models and simulations of optical transmission of microwave frequencies.
Major Commercial Applications	The underlying technologies are driven by demand for high speed digital optical data transmission. COTS developments will, however, need to be tailored and optimized to address unique requirements of microwave transmission.
Affordability Issues	Overall cost of radar development and the logistics of incorporating a new technology are currently barriers. However, the convergence of technologies that allow for encoding of light at microwave frequencies and mixed signal (hybrid analog digital) integrated circuits capable of direct digital processing of microwave signals can be expected to dramatically change the potential cost equation in the near-term.
Export Control References	Products and technologies are not explicitly listed. At the application level, technologies specially designed for distribution or control of microwave energy in a phased array radar would be categorically captured if they could be categorized as “assemblies” for an “electronically steerable phased array antenna,” under CCL Cat 6A008.e (WA Cat 6.A.8.e). Equipment for “development” of equipment, and specially-designed components and devices, and software for the "development," "production," or "use," of such goods for telecommunications applications in CCL Cat 5, Part 1, arguably provides some protection for the underlying technologies. At the same time, the qualification that the technologies must be "specially-designed" for telecommunications would arguably exempt generic components designed for use in, but not exported as part of, an identifiable radar system.

BACKGROUND

There has been interest in optical distribution and control of microwave energy for nearly thirty years. However, one of the limitations was that the technology had inherent limitations on power that made it unsuited for the kinds of corporate feed architectures then available. Only in recent years, with the emergence of other technologies for active phased arrays, allowing distribution and phase control at low RF power levels, have the benefits of this technology become practically realizable. These solid state device advances coupled with the emergence of low noise figure, high dynamic range photonic links enable broadband phased-array radar designs of military interest.

MCTL DATA SHEET 11.8-9. RADAR SIGNAL PROCESSING TECHNOLOGY

Radar signal processing comprises a set of hardware and software techniques for extracting features from radio frequency energy reflected from objects, typically in the presence of interfering signals. Signal processing includes features that can be exploited to detect, classify, or identify specific targets or environmental features of interest.

Critical Technology Parameter(s)	Radar signal processing algorithms providing any one or more of the following features: • Operational implementations of physical predictive models of target or clutter; • Time and geometry varying models of ground, sea, or air targets comprising multiple time and geometry scatterers. (Note: this is intended to exclude simpler physical and mathematical models such as spheres, corner-reflectors, or Swerling case models); • Endoclutter processing and feature extraction, including ground moving target indication from a moving radar; • Electromagnetic counter-countermeasures features; • Real-time adaptive control of the spectral characteristics and spatial distribution of radar transmit/receive signal parameters; and • Real-time prediction of radar performance as a function of meteorological/atmospheric conditions.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	High resolution radars meeting any of the characteristics defined in CCL Cat 6A008.
Unique Software	Experimentally-validated radar cross-section models and simulations of complex targets (aircraft, ground, or marine vehicles) that have been derived from, or have essentially the same characteristics as those of operational or planned military systems. Any predictive first principles physical models having sufficient fidelity and reliability to be used for radar design without extensive testing and validation. Software algorithms that have been specially designed or modified for the detection of uncooperative targets, or for endo-clutter detection of targets.
Major Commercial Applications	At the level of sophistication defined for this technology, civil applications will be limited to a few demanding applications, such as high resolution space-based radar for earth resource monitoring, air traffic control, and weather radar.
Affordability Issues	As a practical matter, given the complex dynamic nature of modern warfare, comprehensive testing of military radar systems is cost prohibitive. Modeling and simulation of the signal processing aspects of radar designs are essential for affordable development of reliable systems.
Export Control References	Software for the "development," "production" or "use" of radar equipment and associated test ranges identified in CCL Cat 6.A.8 and 6.B.8 are categorically controlled by 6.D.1 and 2. Analog digital converters and acoustic wave devices are export controlled in Cat 3 of the WA dual use list and the CCL.

BACKGROUND

The development and global availability of low-cost, high-performance digital microprocessors and digital signal processors has largely obviated the need to build dedicated signal processing equipment. While hardware preprocessing (as a simple example, band-pass filtering) of RF signals is still essential, the know-how for design and fabrication of the essential passive components is now widely available. Only a few countries have the capabilities to do state-of-the-art monolithic millimeter and microwave integrated circuits, and microwave power modules. Accordingly, these remain controlled and are discussed in MCTL Section 8, Electronics Technology. Similarly, technologies for processing features once it has been extracted from physical radar signals and formatted as data for general-purpose information processing is addressed in MCTL Section 10, Information Systems Technology.

While the emphasis in modern radar design is on digital signal processing, some analog and hybrid devices continue to support critical processing functions. These include analog-to-digital converters and bulk and surface acoustic wave devices, also addressed in MCTL Section 8, Electronics Technology.